

Holographic Noise

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Are time and space infinitely smooth?

- Einstein's theory assumes spacetime is a classical manifold, infinitely divisible
- This may be just an approximate behavior
- Can we measure the minimum interval of time?

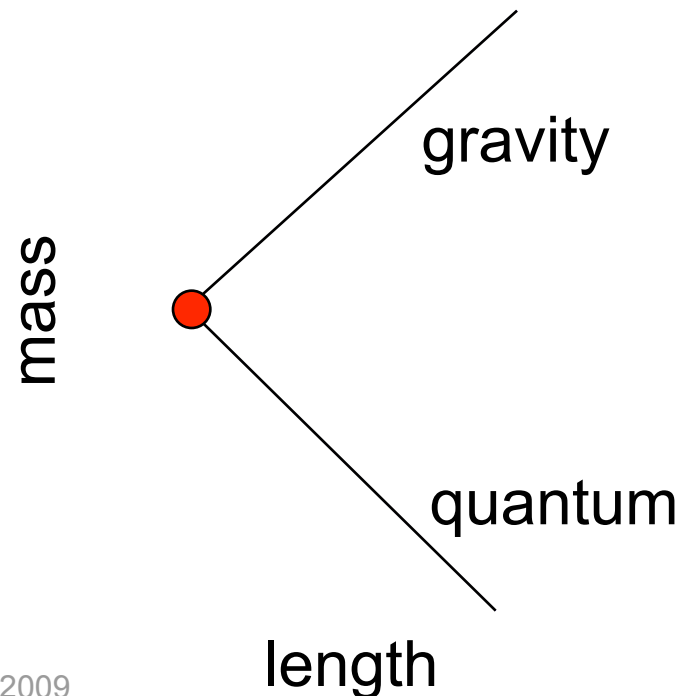
The smallest interval of time

- Quantum gravity suggests a minimum (Planck) time,

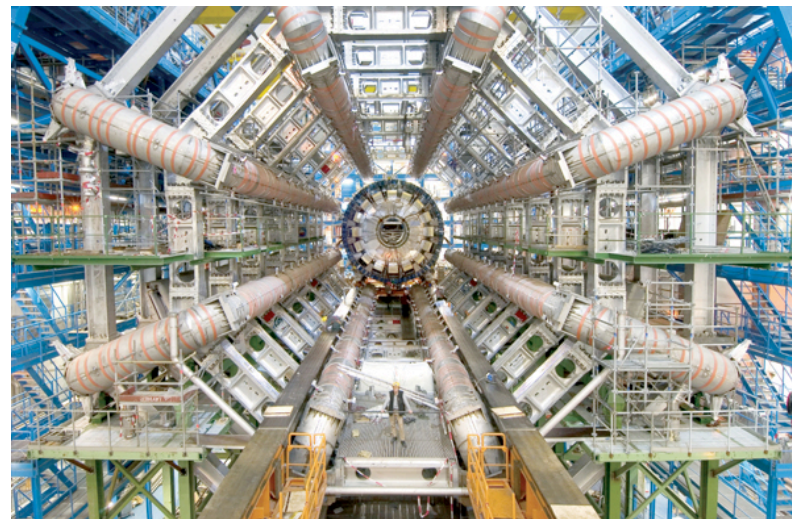
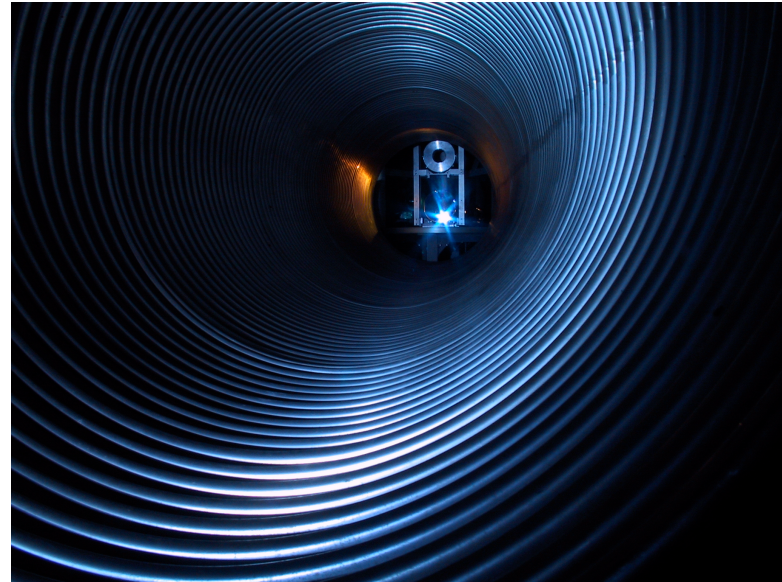
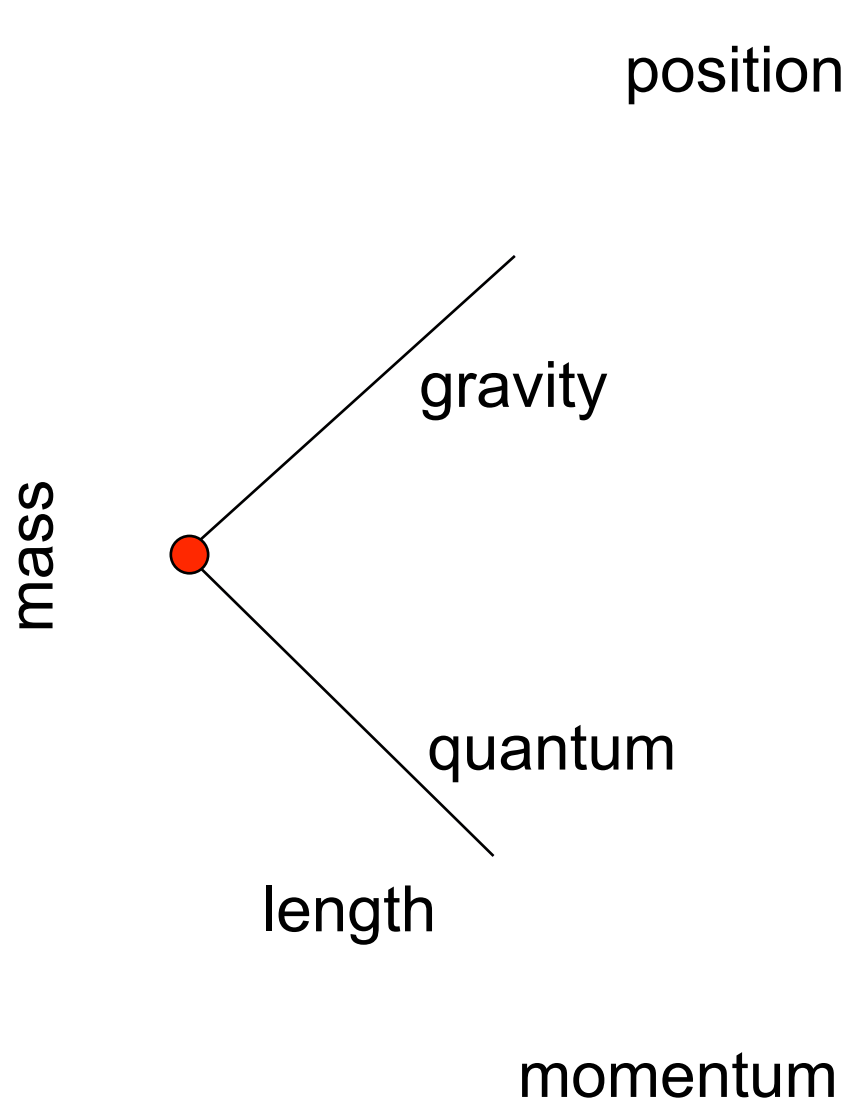
$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \text{ seconds}$$

$$l_P = \sqrt{\hbar G_N/c^3} = 1.616 \times 10^{-33} \text{ cm}$$

- ~ particle energy 10^{16} TeV

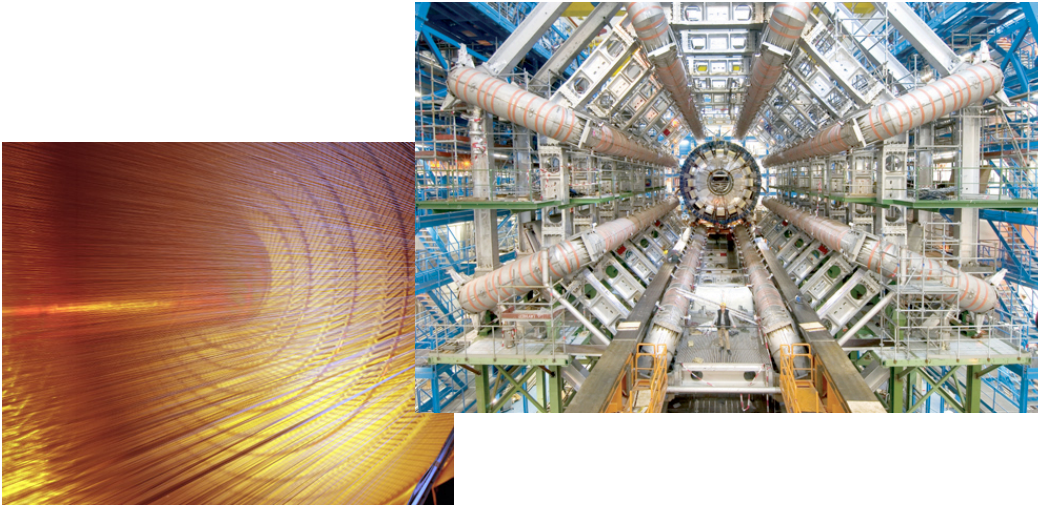


Two approaches to the Planck scale

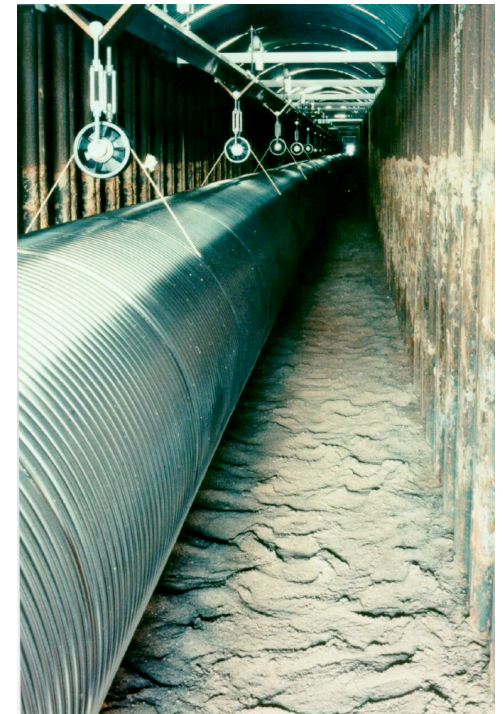


Best microscopes vs best microphones

CERN/Fermilab: $\text{TeV}^{-1} \sim 10^{-18}$ m: particle interactions



LIGO/GE0600: $\sim 10^{-18}$ m, coherent over $\sim 10^3$ m baseline: Positions of massive bodies



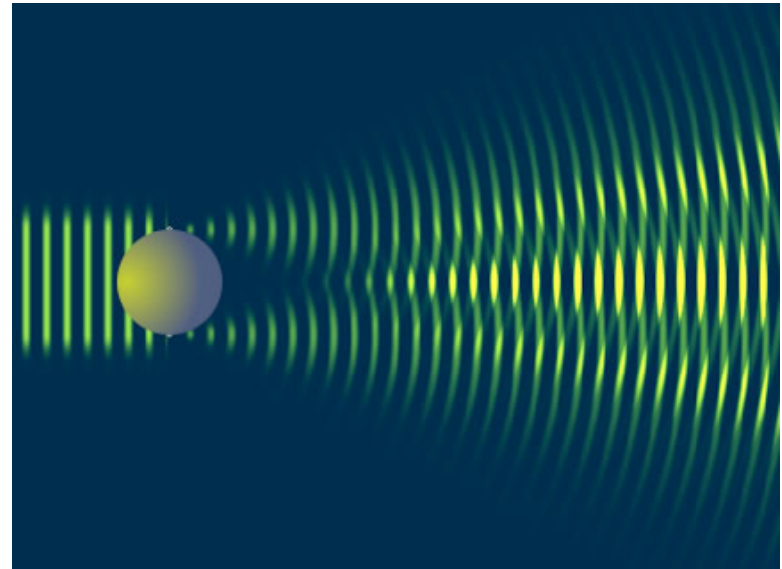
A new phenomenon?: holographic noise

- The minimum interval of time may affect interferometers
- Transverse uncertainty much larger than Planck scale in holographic theories
- precise, zero-parameter prediction of “Holographic Noise”

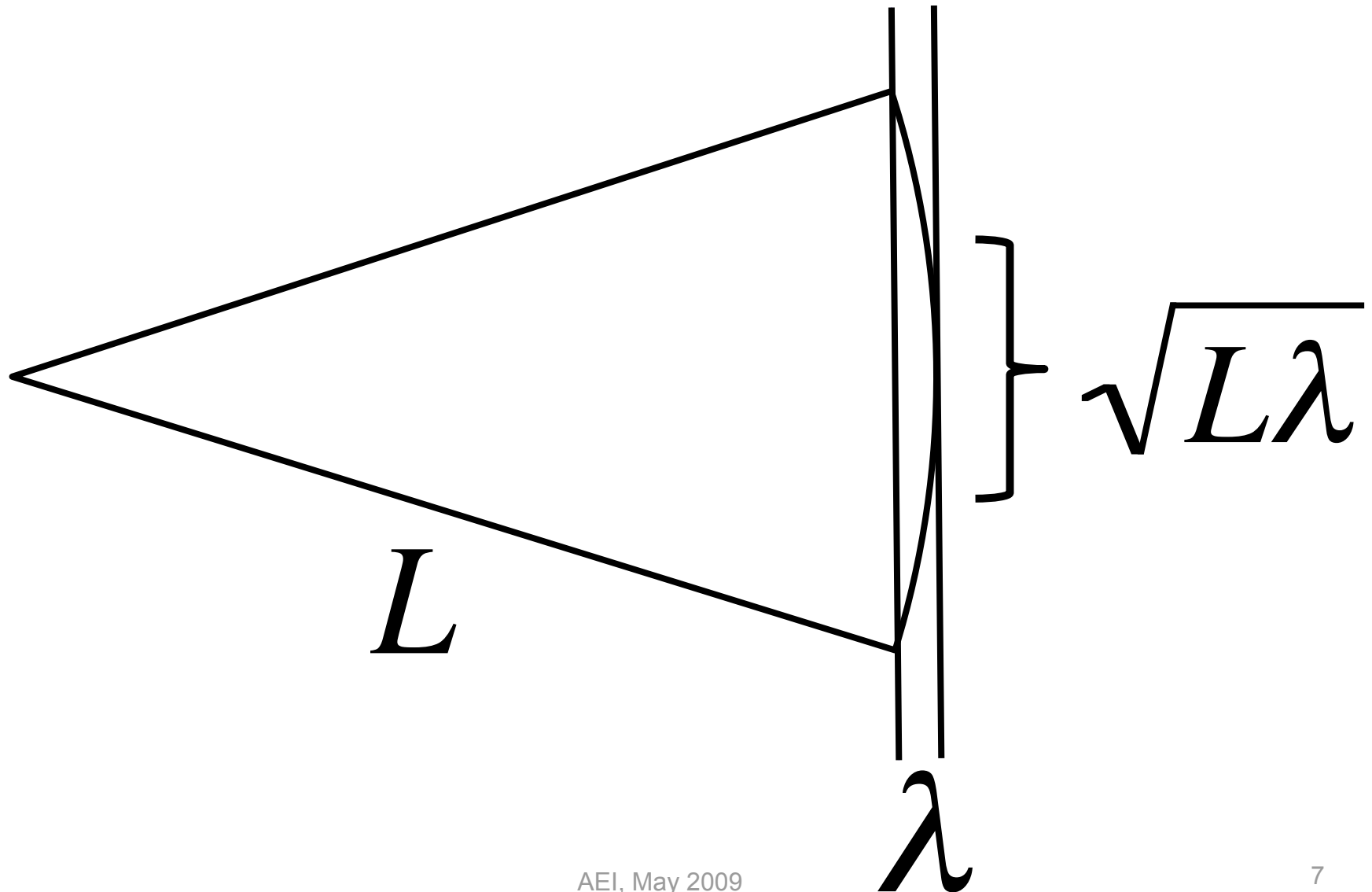
“Planck diffraction limit” at L

$$\Delta x \sim \sqrt{\lambda L}$$

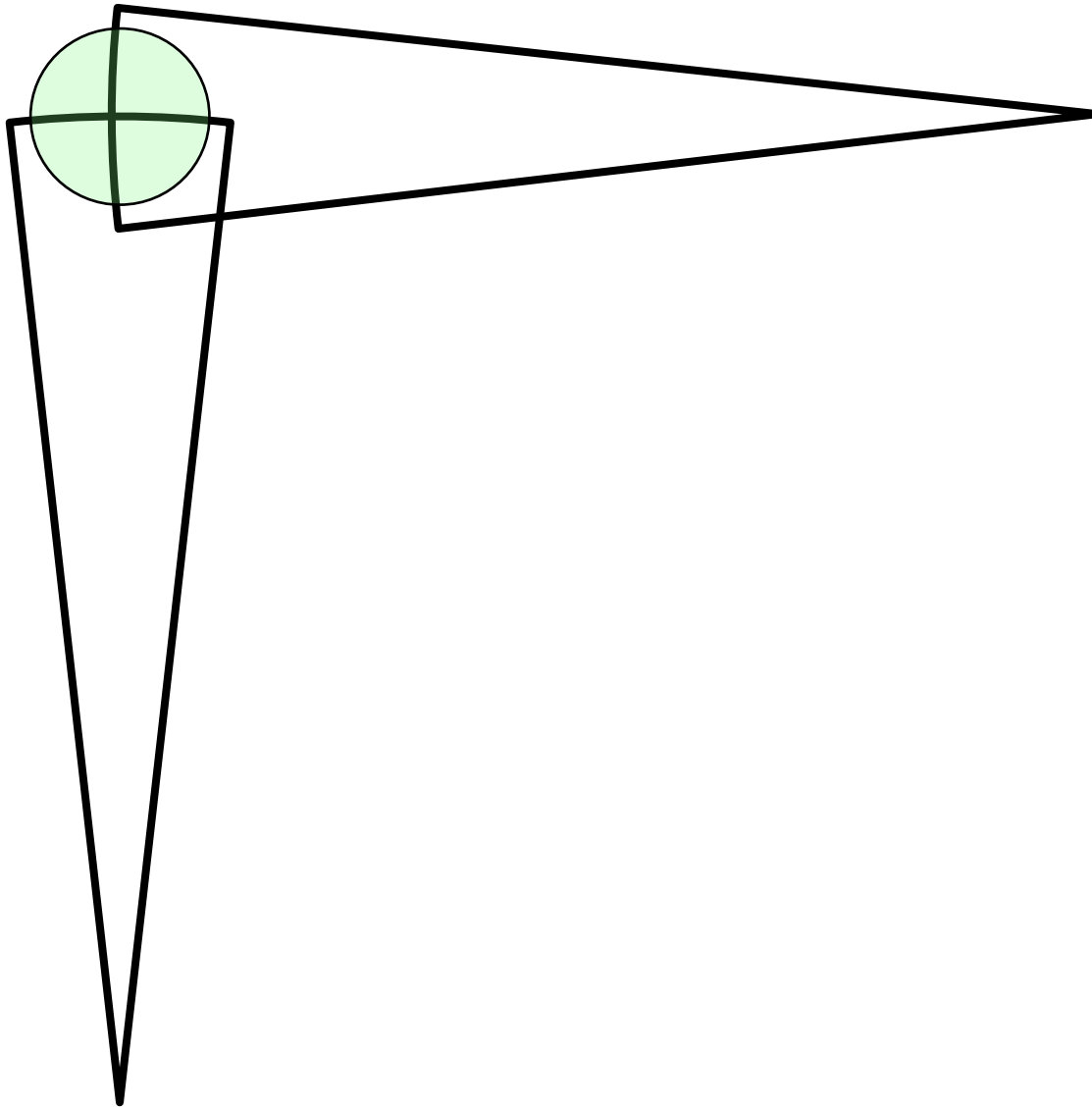
is \gg Planck length



Spatial frequency limit causes transverse indeterminacy:
transverse position wavefunction at distance L



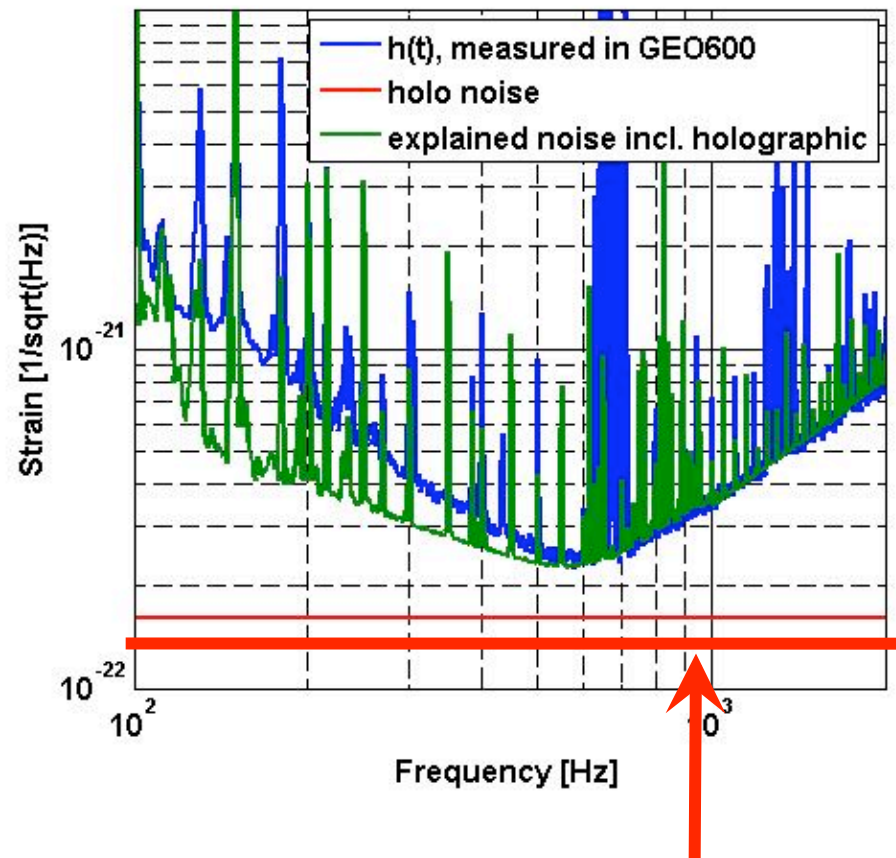
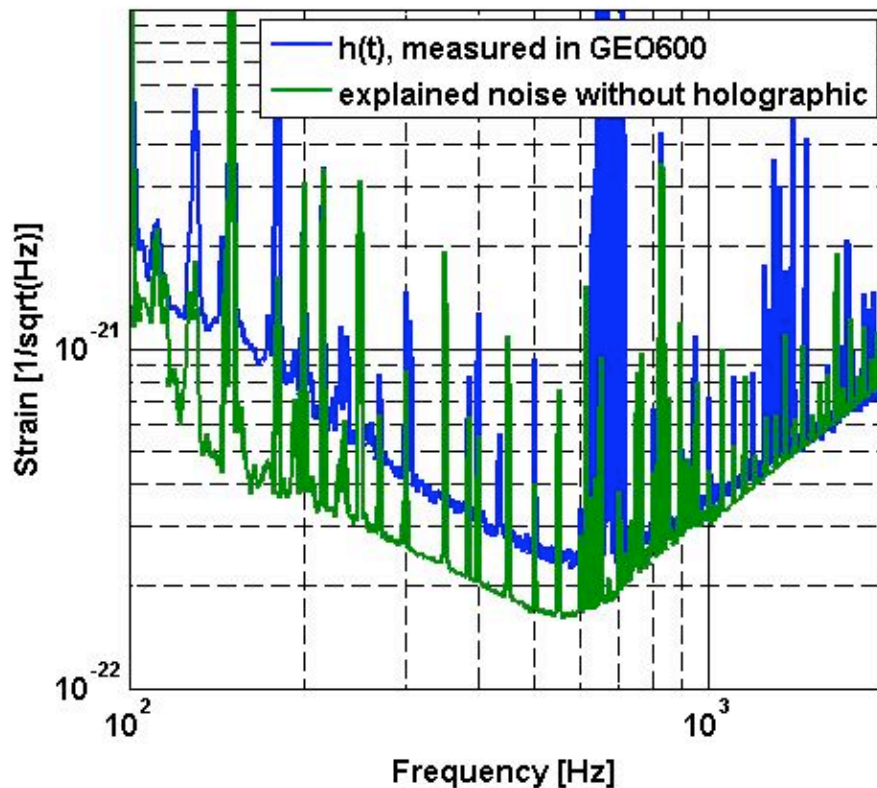
Indeterminacy in difference of orthogonal transverse positions



GEO-600 (Hannover): best displacement sensitivity



“Mystery Noise” in GEO600



Data: S. Hild (GEO600)

Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

Total noise: not fitted

AEI, May 2009

$$\sqrt{t_{Planck} / \pi}$$

zero-parameter prediction for
holographic noise in GEO600
(equivalent GW strain)

Measurement of holographic noise

- Holographic wave geometry predicts a new detectable effect: "holographic noise"
- Not the same as zero-point field mode fluctuations
- Spectrum and distinctive spatial character of the noise is predicted with no parameters
- It may already be detected
- An experimental program is motivated

CJH: [arXiv:0806.0665](#) Phys Rev D.78.087501 (2008)

CJH: [arXiv:0712.3419](#) Phys Rev D 77, 104031 (2008)

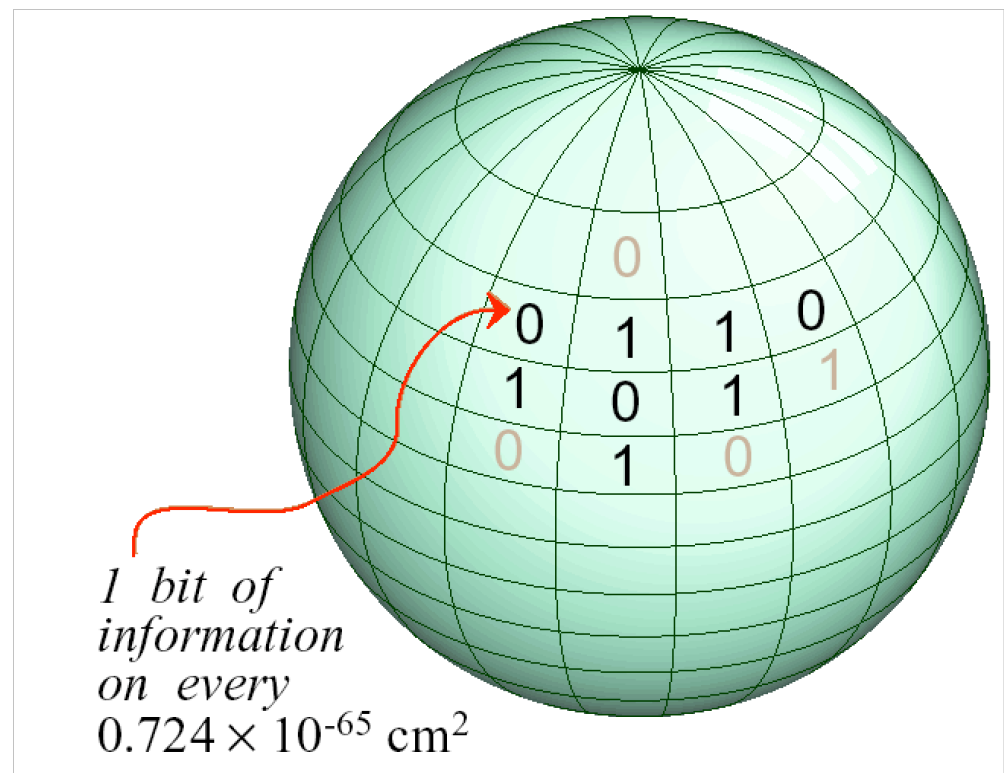
CJH and M. Jackson, Phys. Rev. D in press, arXiv:0812.1285

Holographic Theories of Everything

“This is what we found out about Nature’s book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size.”

-Gerard 't Hooft

Everything about the 3D world can be encoded on a 2D null surface at Planck resolution



Holographic geometry: a phenomenological layer

Fundamental theory (Matrix, string, loop,...)



Holographic geometry (paraxial waves, diffraction, transverse spacetime wavefunction, holographic uncertainty...)



Observables in classical apparatus (effective beamsplitter motion, holographic noise in interferometer signals)

Holographic Quantum Geometry: theory

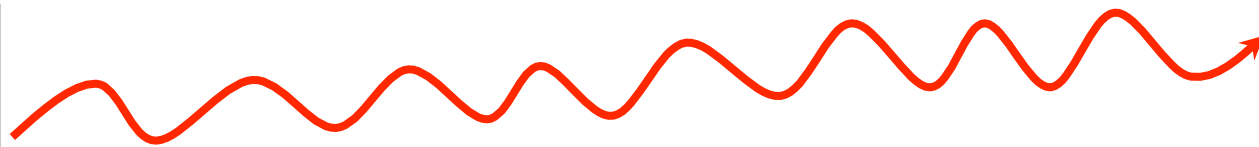
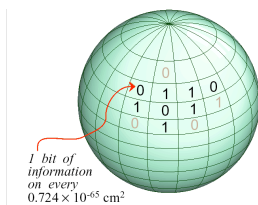
- Black holes: entropy=area/4 $S = A/l_P^2 4 \ln 2$
- Black hole evaporation
- Einstein's equations from heat flow
- Classical GR from surface theory
- Universal covariant entropy bound
- Exact state counts of extremal holes in large D
- AdS/CFT type dualities: N-1 dimensional duals
- Matrix theory
- All suggest theory on 2+1 dimensional null surfaces with Planck frequency bound

Holography 1: Black Hole Thermodynamics

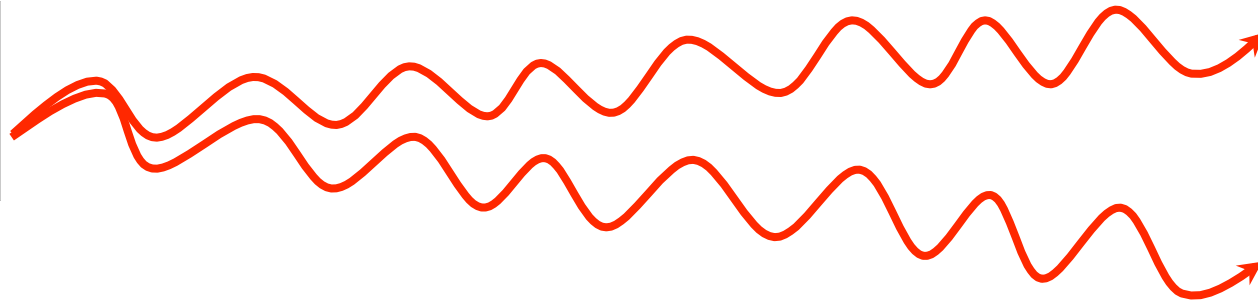
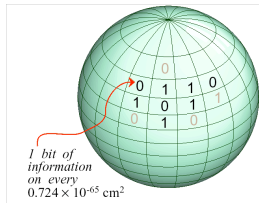
- Beckenstein, Bardeen et al. (~1972): laws of black hole thermodynamics
- Area of (null) event horizon, like entropy, always increases
- Entropy is identified with $1/4$ of event horizon **area** in Planck units (not volume)
- Is there is a deep reason connected with microscopic degrees of freedom of spacetime encoded on the surface?

Holography 2: Black Hole Evaporation

- Hawking (1975): black holes radiate ~thermal radiation, lose energy and disappear
- evaporated quanta carry off degrees of freedom (~ 1 per particle) as area decreases
- States on 2D event horizon completely account for information of evaporated states, assembly histories
- Information of evaporated particles = entropy of hole = $A/4$

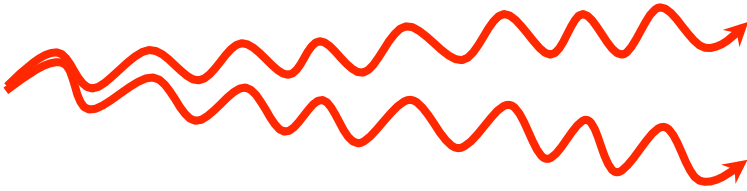
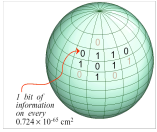


black hole evaporation can obey quantum mechanics if distant, nearly flat space has transverse indeterminacy



If the quantum states of the evaporated particles allowed relative transverse position observables with arbitrary angular precision, at large distance they would contain more information than the hole

Holographic uncertainty and black hole evaporation



$$(L / \Delta x)^2 < (R / \lambda)^2$$

- ~ One particle evaporates per Planck area
- position recorded on film at distance L
- wavelength ~ hole size R
- standard position uncertainty

$$\Delta x > R$$

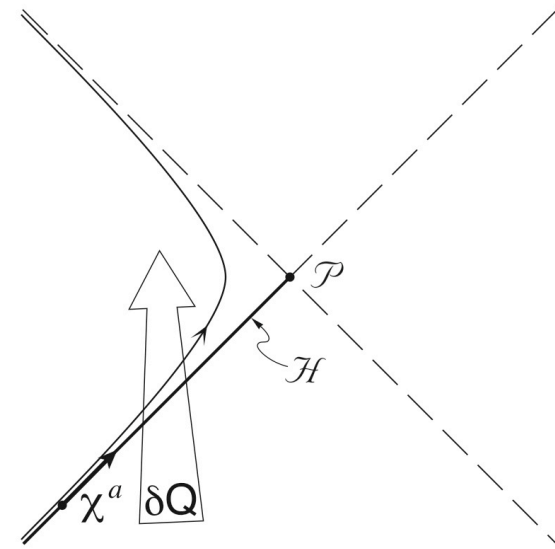
- Particle images on distant film: must have fewer “pixels” than hole
- Requires transverse uncertainty at distance L independent of R

$$\Delta x > \sqrt{\lambda L}$$

- **Uncertainty of flat spacetime independent of black hole mass**
- Similarly for number of position states of an interferometer

Holography 3: nearly-flat spacetime

- Unruh (1976): Hawking radiation seen by accelerating observer
- Appears with any event horizon, not just black holes: identify entropy of thermal radiation with missing information
- Jacobson (1995): Einstein equation derived from thermodynamics (\sim equation of state)
- Classical GR from 2+1D null surface (Padmanabhan 2007)



Holography 4: Covariant (Holographic) Entropy Bounds

- 't Hooft (1985): black holes are quantum systems
- 't Hooft, Susskind et al. (~1993): world is "holographic", encoded in 2+1D at the Planck scale
- Black hole is highest entropy state (per volume) and sets bound on entropy of any system (includes quantum degrees of freedom of spacetime)
- All physics within a 3D volume can be encoded on a 2D bounding surface ("holographic principle")
- Bousso (2002): holographic principle generalized to "covariant entropy bound" based on causal diamonds: entropy of 3D light sheets bounded by area of 2D bounding surface in Planck units
- Suggests that 3+1D geometry emerges from a quantum theory in 2+1D: light sheets

Holography 5: Exact dual theories in $N-1$ dimensions

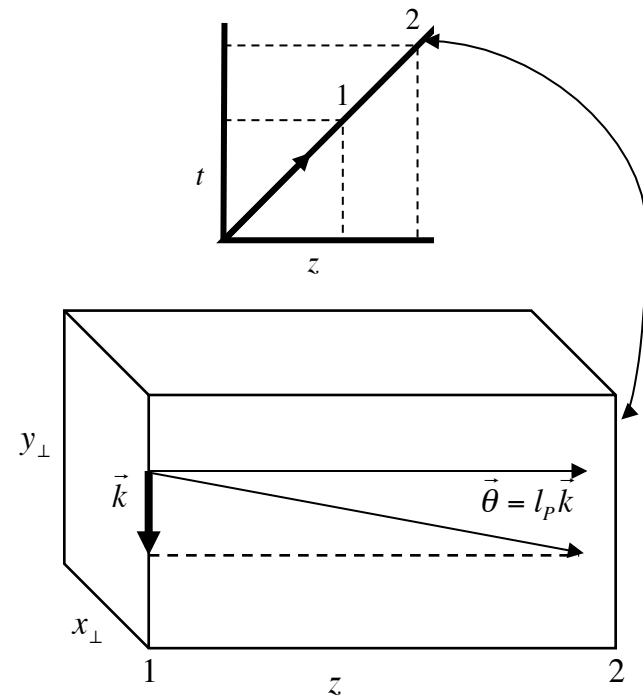
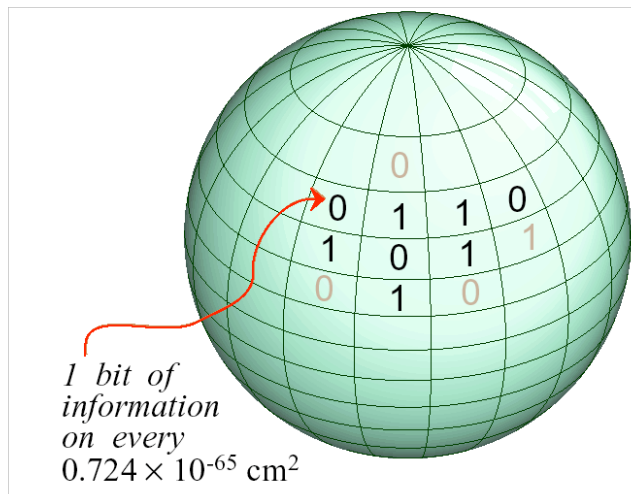
- Maldacena, Witten et al. (1997...): AdS/CFT correspondence
- N dimensional conformal field "boundary" theory exactly maps onto (is dual to) $N+1$ dimensional "bulk" theory with gravity and supersymmetric field theory
- Is nearly flat $3+1$ spacetime described as a dual in $2+1$?

Holography 6: string/M theory

- Strominger, Vafa (1996): count degrees of freedom of extremal higher-dimension black holes using duality
- All degrees of freedom appear accounted for
- Agrees with Hawking/Beckenstein thermodynamic count
- Unitary quantum system
- Strong indication of a minimum length \sim Planck length
- What do the degrees of freedom look like in a realistic system?
- Matrix theory: wavefunctions of transverse position Matrix Hamiltonian (CJH& M. Jackson)

Holographic geometry implements holographic entropy bound in emergent 3+1D spacetime

- 3+1D spacetime from 2+1D
- built on light sheets: covariant formulation
- fewer independent modes than field theory
- independent pixels in 3D volume \sim area of 2D null surface element
- “bandwidth limit” of spacetime states



Theories with holographic noise

Two conditions are sufficient:

1. Maximum Planck frequency in any frame
2. Planck wavelength resolution on light sheets

1D segment of length L on
null wavefront

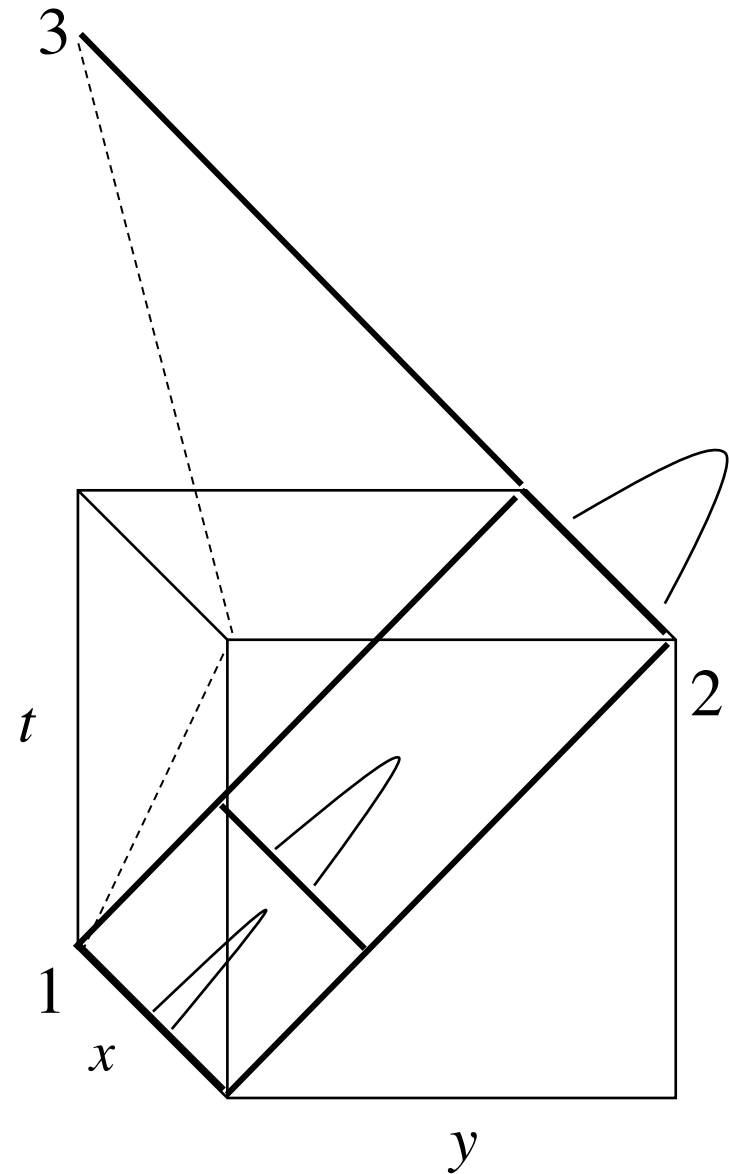
Sweeps out 2D surface:

$$(L / \Delta x)^2 \approx L / l_P$$

independent position
degrees of freedom

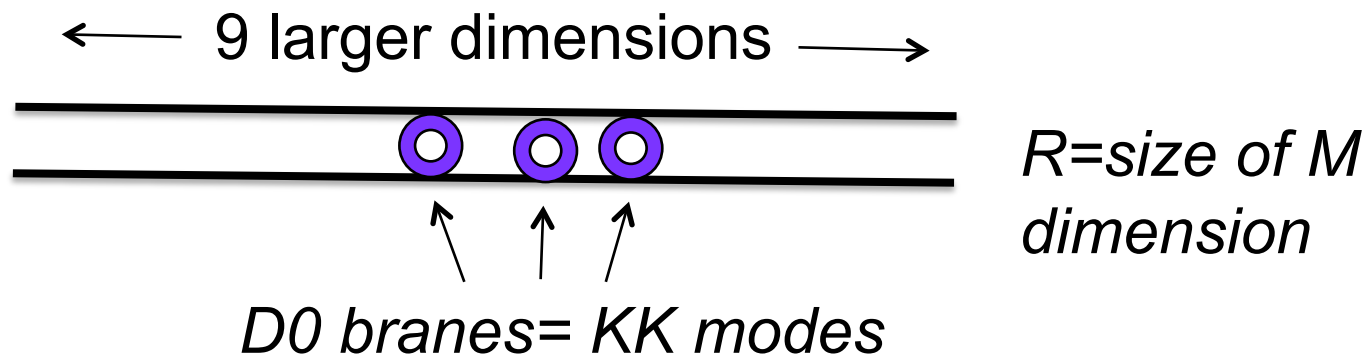
Position variance in 2D

$$\Delta x^2 \approx L l_P$$



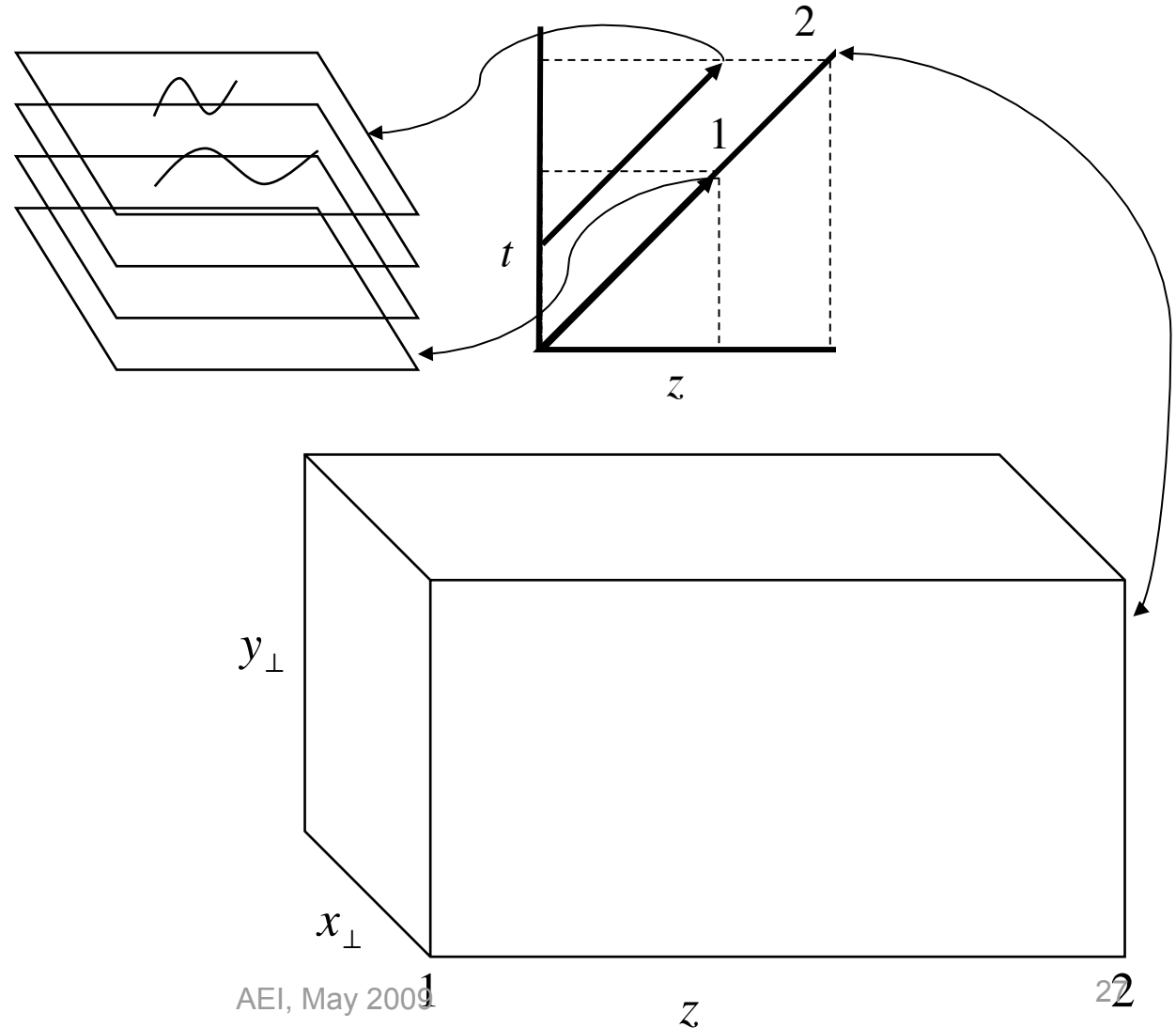
Example: Matrix theory

- Banks, Fischler, Shenker, & Susskind 1997: a candidate theory of everything
- Fundamental objects are $N \times N$ matrices, describing N “D0 branes” (particles)
- Dual relationship with string theory
- Gives rise to 10 space dimensions, 1 compact, plus time



- Only 2 of the 9 space dimensions survive to be macroscopic
- The third space dimension is virtual, swept out by 2D null sheet

*3+1D spacetime
emerges from
2+1D: light
sheet with $z=t$*



Holographic spacetime: wave theory from M theory

- N D0 branes, N x N matrices X_i , $i= 1$ to 9, compact M dimension with radius $R \sim$ Planck length
- Hamiltonian from Banks, Fischler, Shenker, & Susskind:

$$H = R \operatorname{tr} \left\{ \frac{\Pi_i \Pi_i}{2} + \frac{1}{4} [X_i, X_j]^2 + \theta^T \gamma_i [\theta, X_i] \right\}$$

- Notions of position, distance emerge on scales $\gg R$
- local in 2+1 D, “incompressible” on Planck scale: holographic
- Center of mass position of macroscopic body, $x = \operatorname{tr} X$
- Macroscopic longitudinal position encoded by first (kinetic) term, conjugate momenta to position matrices

CJH & M. Jackson, arXiv:0812.1285

Macroscopic wave equation from M theory

- M Hamiltonian stripped to macroscopic essentials

$$\hat{H} = \frac{R}{2\hbar} \text{tr} \hat{\Pi}^2$$

- substitute

$$R \rightarrow k^{-1} = \lambda/2\pi$$

$$\text{tr} \hat{\Pi}^2 \rightarrow -\hbar^2 \partial^2 / \partial x^2,$$

$$\hat{H} \rightarrow i\hbar \partial / \partial z^+,$$

Macroscopic wave equation from M theory

$$\hat{H} = \frac{R}{2\hbar} \text{tr} \hat{\Pi}^2$$

becomes

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z^+} = 0$$

- Schrodinger equation, with z^+ as time dimension
- Quantum mechanics without Planck's constant

Solutions of wave equation mix dimensions

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z^+} = 0$$

Solutions display diffusion, diffraction:

$$u(x, z^+) = \sum_{k^\perp} A_{k^\perp} \exp -i[k^+ z^+ \pm k^\perp x]$$

$$k^\perp = \sqrt{4\pi k^+ / \lambda}$$

New uncertainty principle: widths of wavepackets

$$\frac{\partial^2 u}{\partial x^2} + \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z^+} = 0$$

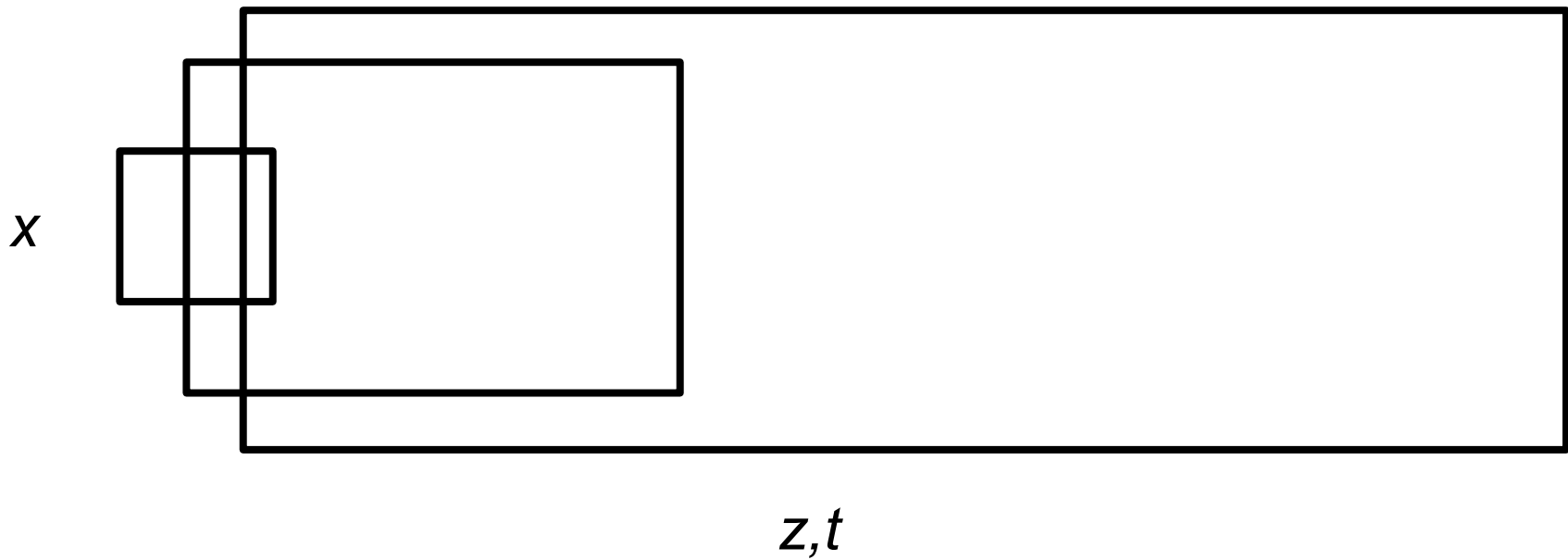
$$\langle \Delta x^2 \rangle \langle \Delta k^{\perp 2} \rangle \geq 16\pi^2$$

$$\Delta L^+ \equiv (4\pi/\lambda)(2\pi/\langle \Delta k^{\perp 2} \rangle)$$

$$\langle \Delta x^2 \rangle > \lambda \Delta L^+ / 2$$

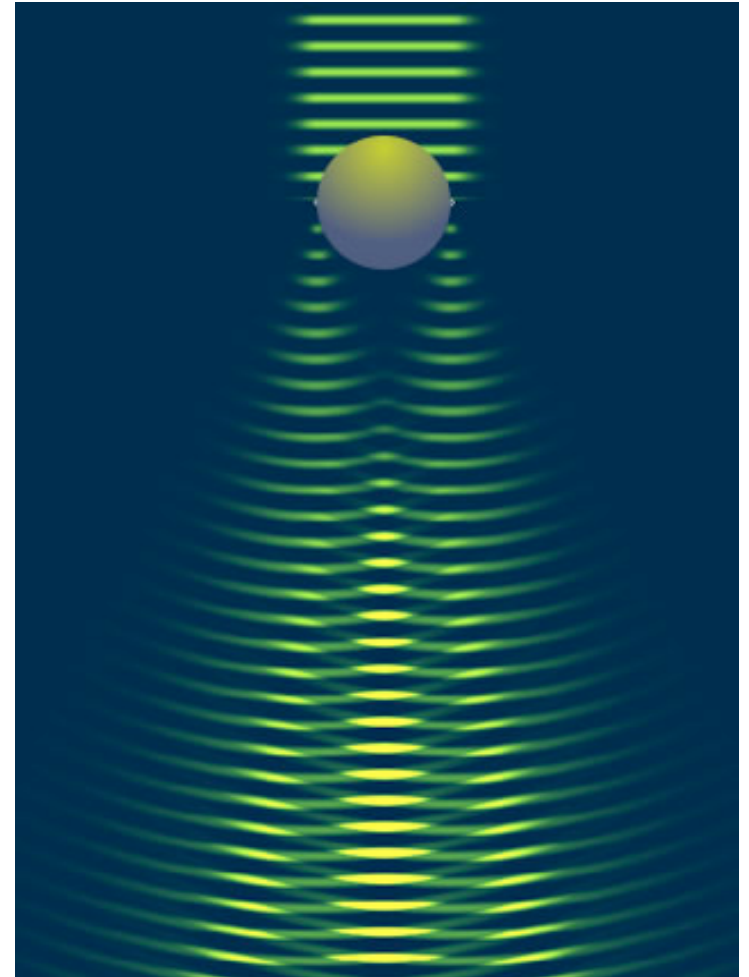
Nonlocal modes connect longitudinal and transverse positions

- Wave solutions: “Holographic geometry”
- Transverse gaussian beam solutions from wave optics
- New macroscopic behavior, not the same as field theory limit



Wave Theory of Spacetime

- Adapt wave optics to theory of “spacetime wavefunctions”
- transverse indeterminacy from diffraction of Planck waves
- Allows calculation of holographic noise with no parameters



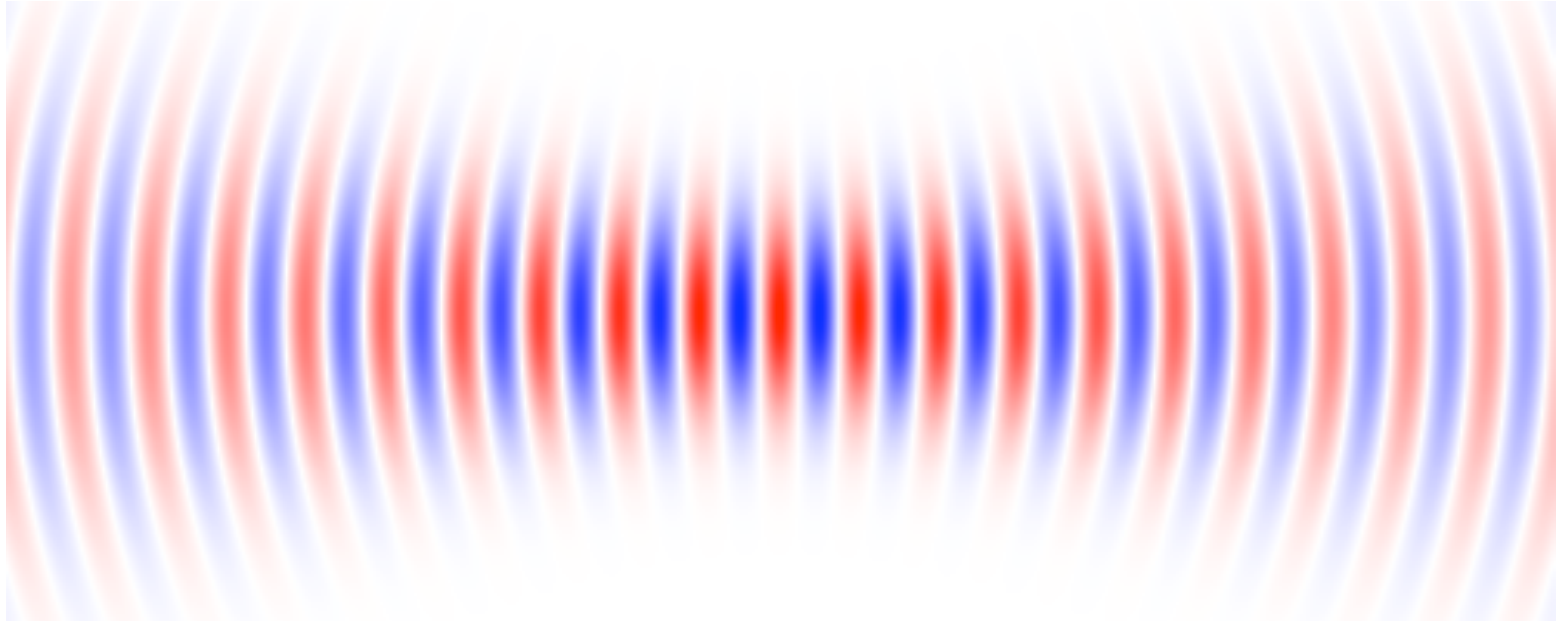
Paraxial wave equation

- phasors in wavefronts: wavefunction relative to carrier
- wave equation in each transverse dimension x

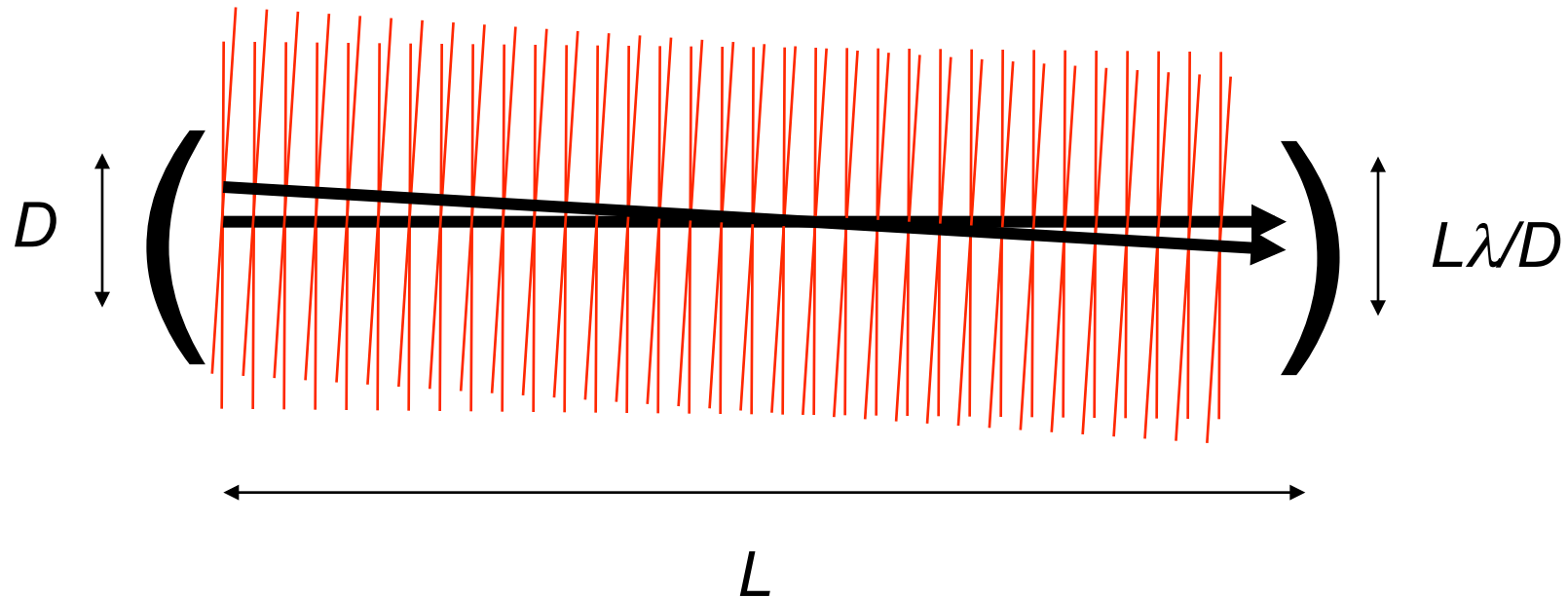
$$\frac{\partial^2 u}{\partial x^2} - \frac{4\pi i}{\lambda} \frac{\partial u}{\partial z} = 0$$

- Basis of laser wave optics
- Solutions display diffraction: e.g. laser cavities
- reinterpret as a position wavefunction

Gaussian Beam solutions



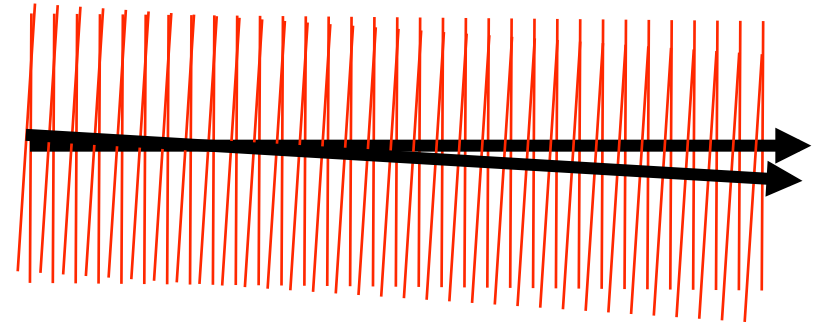
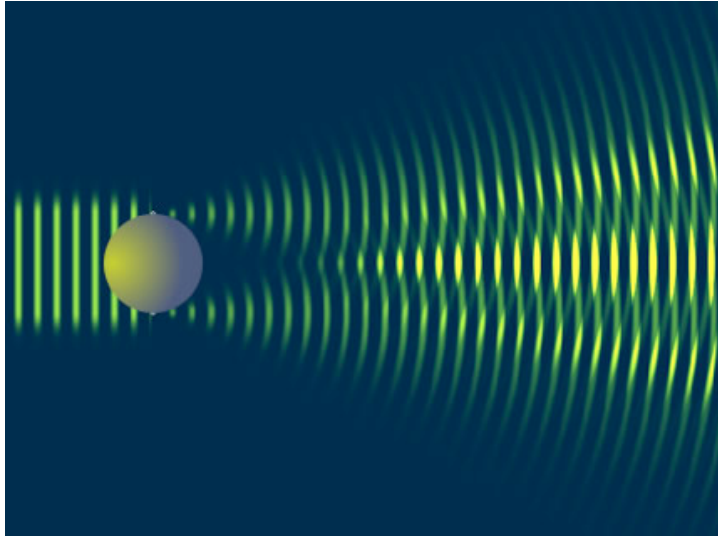
Rayleigh range and uncertainty of rays



- Aperture D , wavelength λ : angular resolution λ/D
- Size of diffraction spot at distance L : $L\lambda/D$
- path is determined imprecisely by waves
- Minimum uncertainty at given L when aperture size = spot size, or

$$D = \sqrt{\lambda L}$$

Indeterminacy of a Planckian path



- Classical spacetime manifold defined by paths and events
- path ~ ray approximation of wave
- Indeterminacy of geometry reflects limited information content of band-limited waves

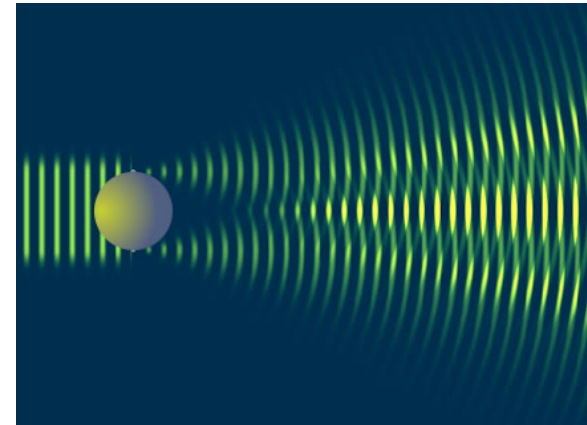
holographic approach to the classical limit

- **Angles** are indeterminate at the Planck scale, and become better defined at larger separations:

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

- But uncertainty in **relative transverse position increases** at larger separations:

$$\Delta x_{\perp}^2 > l_P L$$



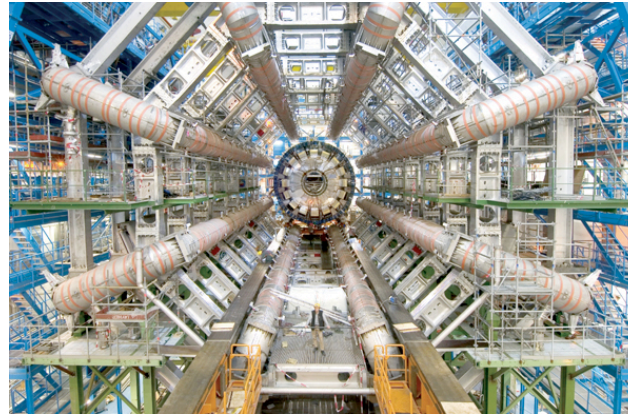
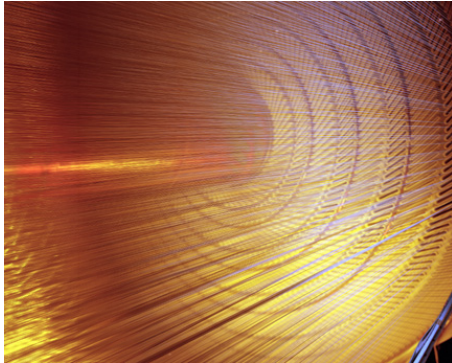
- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

Holographic Noise in Interferometers

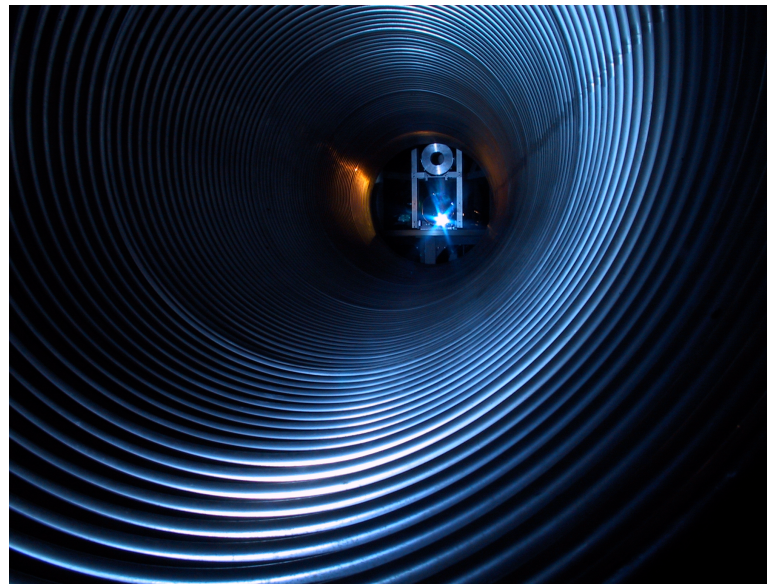
- Nonlocality: relative positions at km scale
- Fractional precision: angle $< 10^{-21}$, $>$ "halfway to Planck"
- Transverse position measured in Michelson layout
- Heavy proof masses, small Heisenberg uncertainty (SQL): positions measure spacetime wavefunction
- holographic noise appears in signal

Measurement of holographic geometry requires coherent transverse position measurement over macroscopic distance

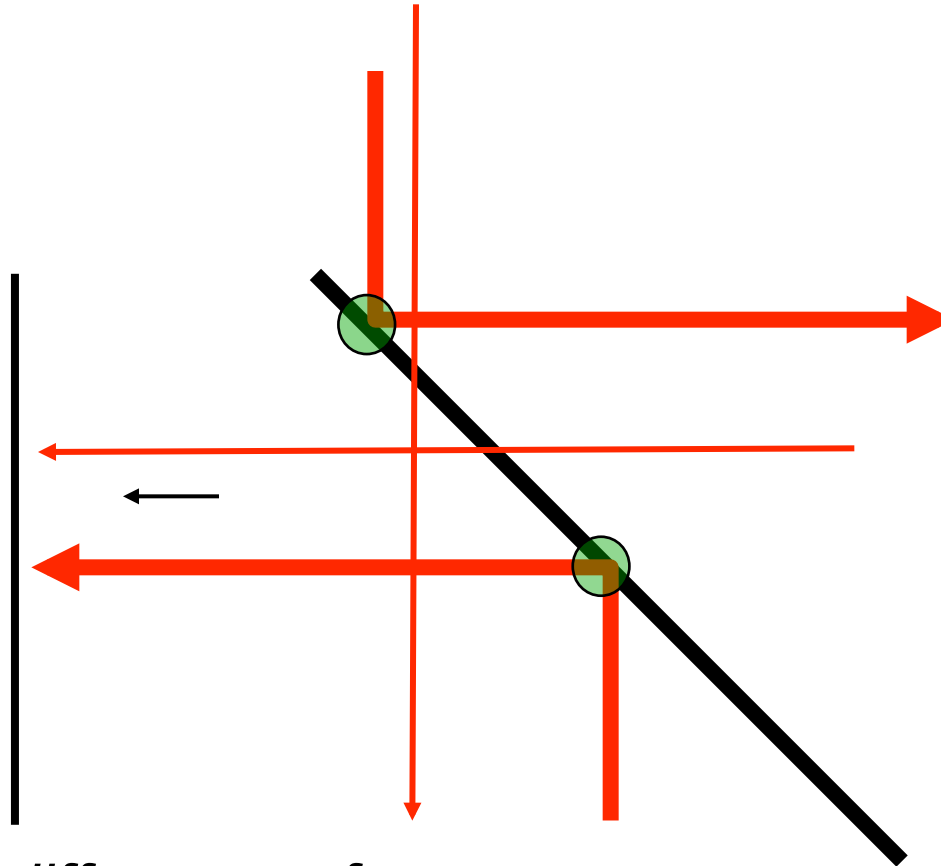
CERN/FNAL: $\text{TeV}^{-1} \sim 10^{-18} \text{ m}$



LIGO/GEO600: $\sim 10^{-18} \text{ m}$
over $\sim 10^3 \text{ m}$ baseline



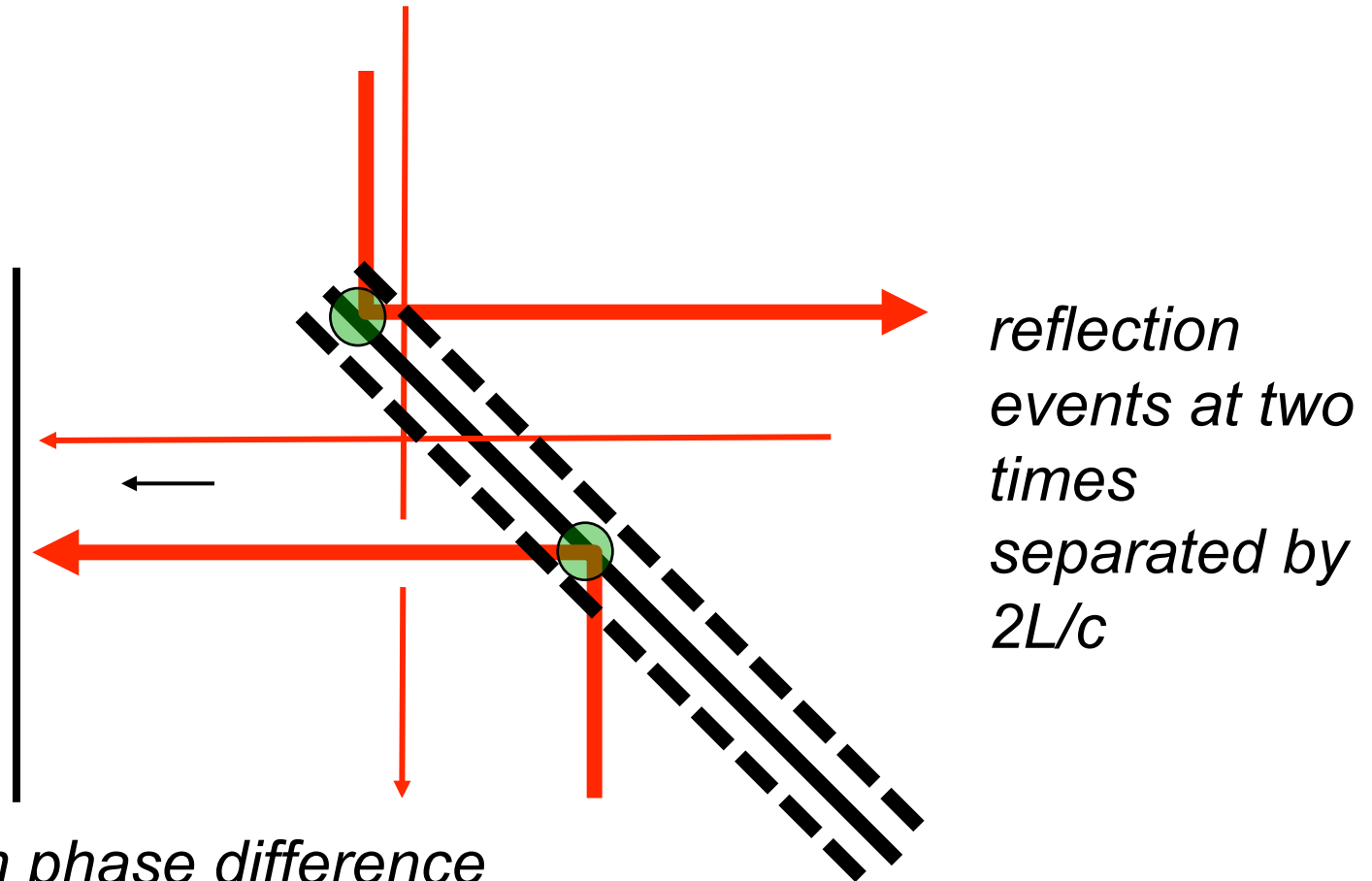
Beamsplitter and signal in Michelson interferometer



*Signal phase ~ difference of
integrated distance along two
orthogonal arms*

Beamsplitter

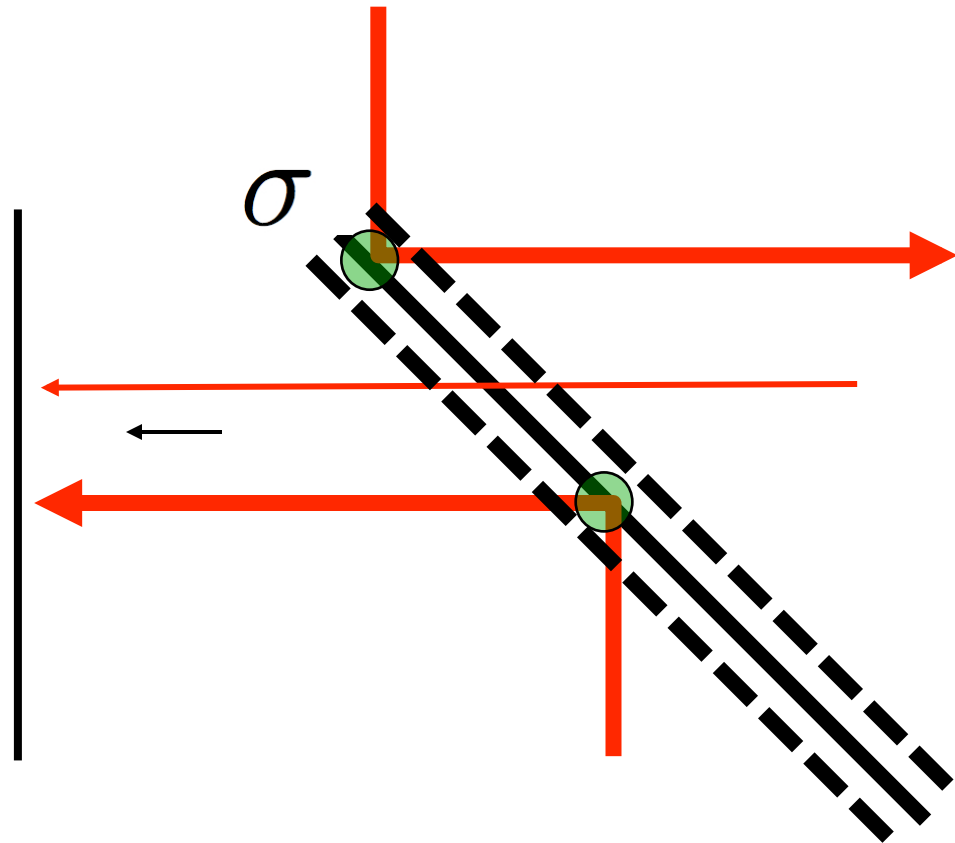
Holographic noise in the signal of a Michelson interferometer



Signal: random phase difference of reflection events from indeterminate position difference of beamsplitter at the two events

Quantum uncertainty of transverse positions of beamsplitter

- Position wavefunction widths of beamsplitter at reflection events given by Gaussian beamwidth
- apparent arm length difference is a random variable, with variance



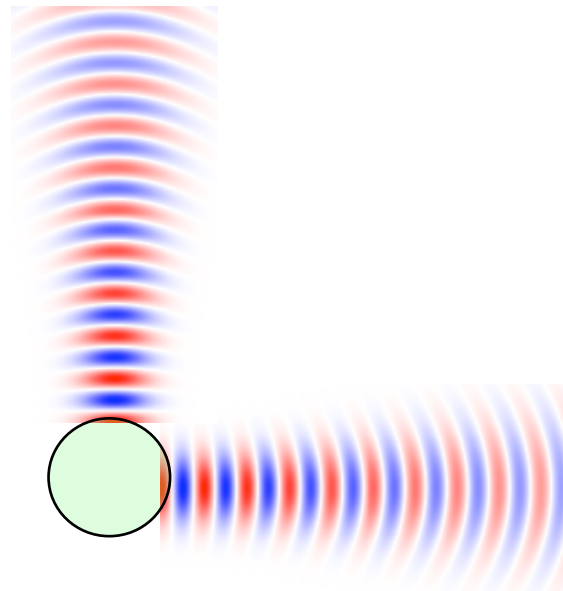
$$L\lambda / \pi$$

this is a new effect predicted with no parameters

Wavefunction and wavefronts

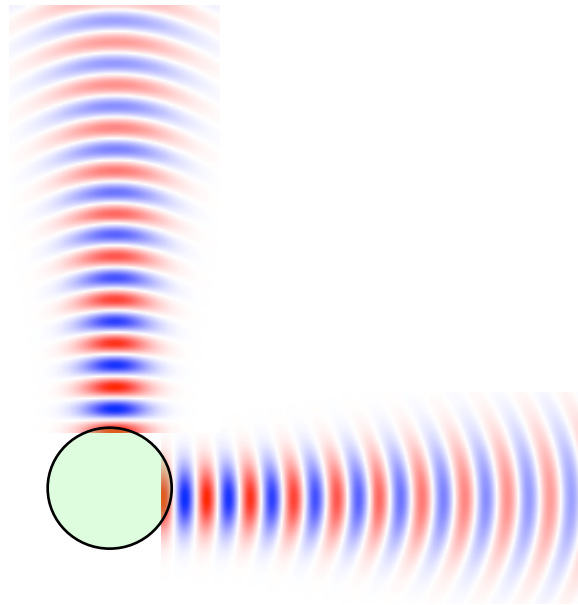
In an optical cavity of any size, the holographic transverse uncertainty is smaller than the beam waist by a factor

$$\sqrt{\lambda_P / \lambda_{laser}}$$



Interferometer with Planck radiation

- Beamsplitter mass limited to Planck surface density
- No “better measurement” is possible



Power Spectral Density of Shear Noise

Uncertainty in angle \sim dimensionless shear

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

At $f=c/2L$, shear fluctuations with power spectral density

$$h_H^2 \simeq L\Delta\theta^2 \approx t_P$$

Universal Holographic Noise

*flat power spectral density of **shear** perturbations:*

$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22} \text{Hz}^{-1/2}$$

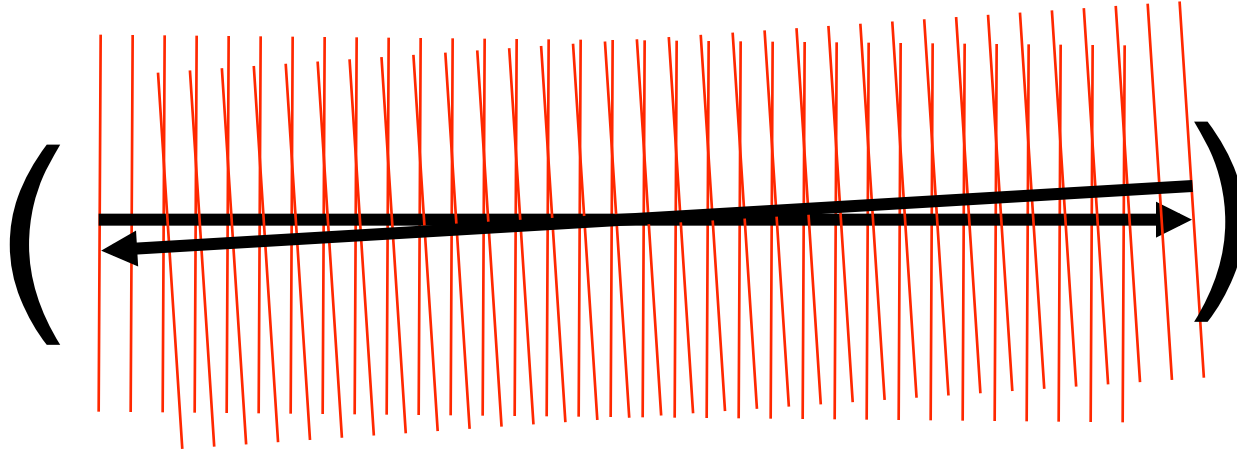
- general property of holographic quantum geometry
- Prediction of spectrum with no parameters
- Prediction of spatial shear character: only detectable in nonlocal relative transverse position observables
- Definitively falsifiable
- Better estimate at low frequencies in interferometers:

$$h(f) = \mathcal{N}^{-1} \sqrt{\Phi/L^2} = \mathcal{N}^{-1} 2\sqrt{t_P/\pi} = \mathcal{N}^{-1} 2.6 \times 10^{-22} / \sqrt{\text{Hz}}$$

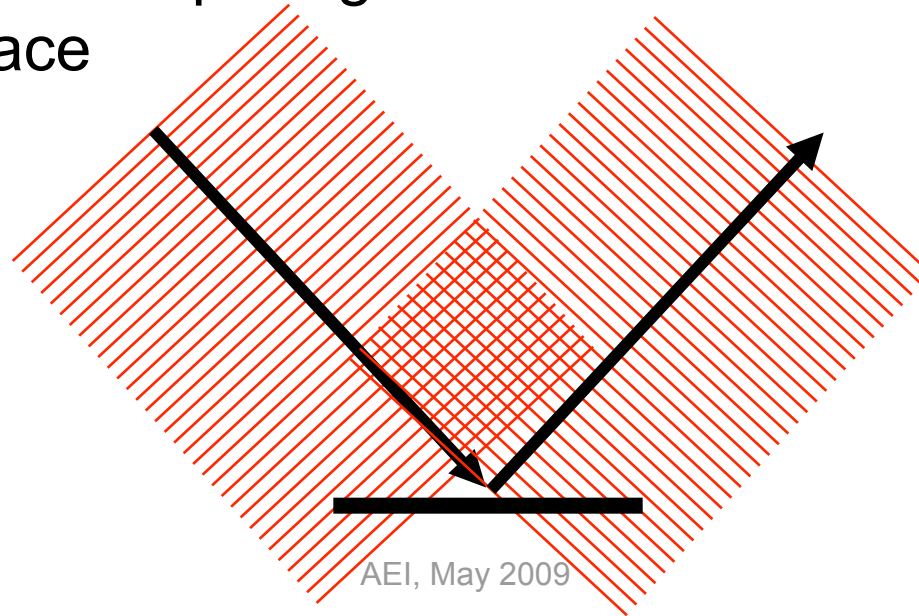
Holographic noise does not carry energy or information

- ~ classical gauge mode (flat space, no classical spacetime degrees of freedom excited)
- ~ sampling or pixelation noise, not thermal noise
- Bandwidth limit of spacetime relationships
- Necessary so the number of distinguishable position states does not exceed holographic bound on degrees of freedom
- No curvature
- no strain, just shear
- no detectable effect in a purely radial measurement

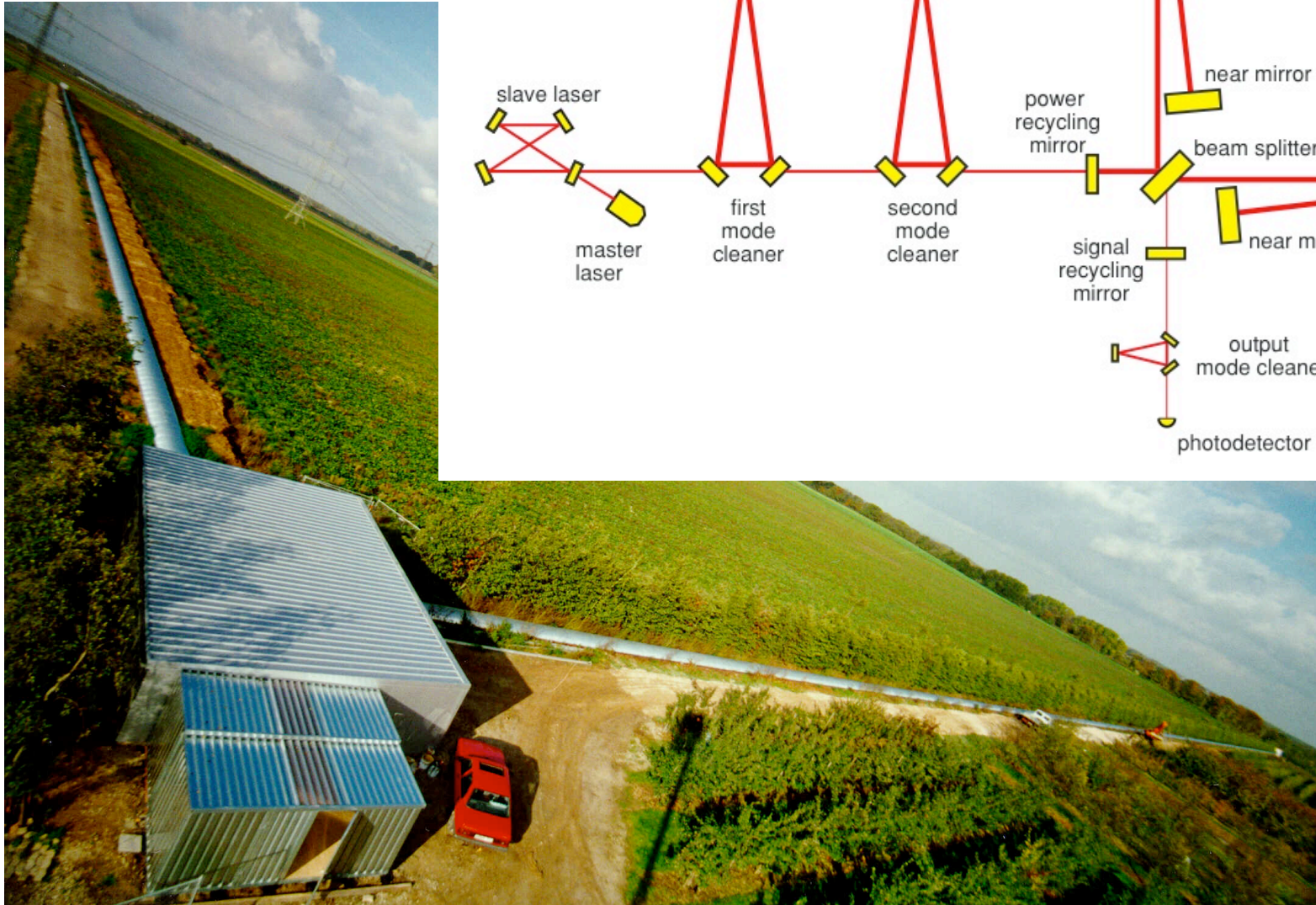
Normal incidence optics: phase signal does not record the transverse position of a surface



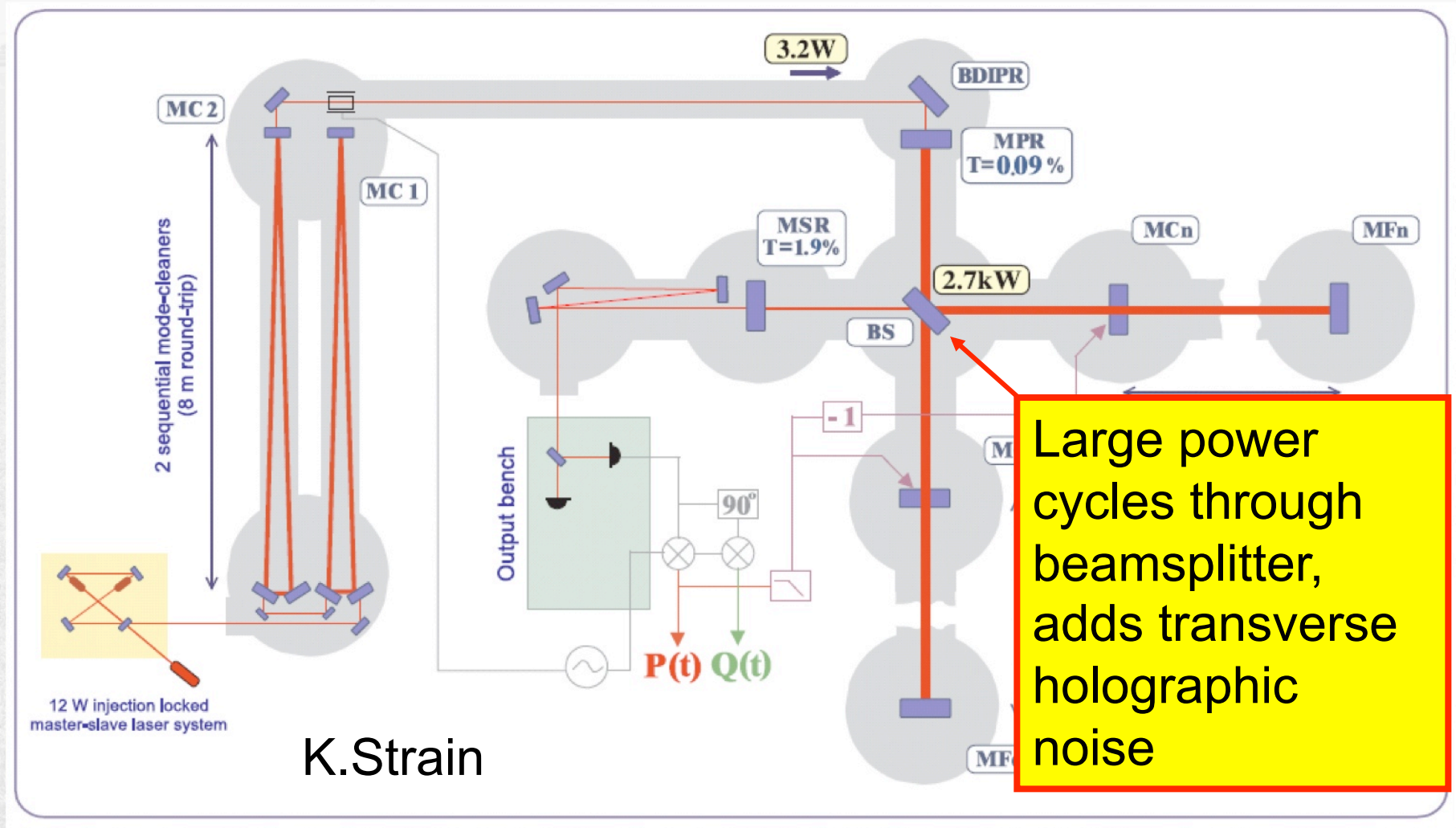
- But phase of beam-split signal is sensitive to transverse position of surface



GEO-600 (Hannover)



The GEO600 Interferometer

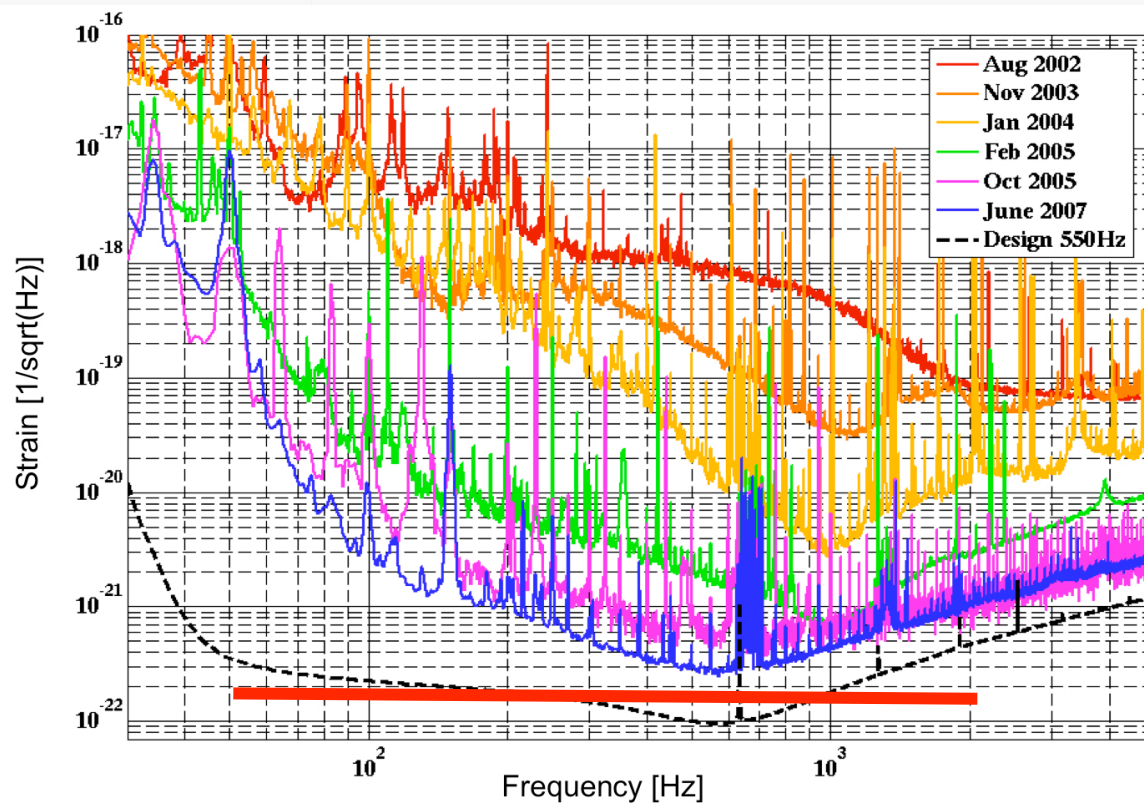


Noise in GEO600 over time



GEO Sensitivities

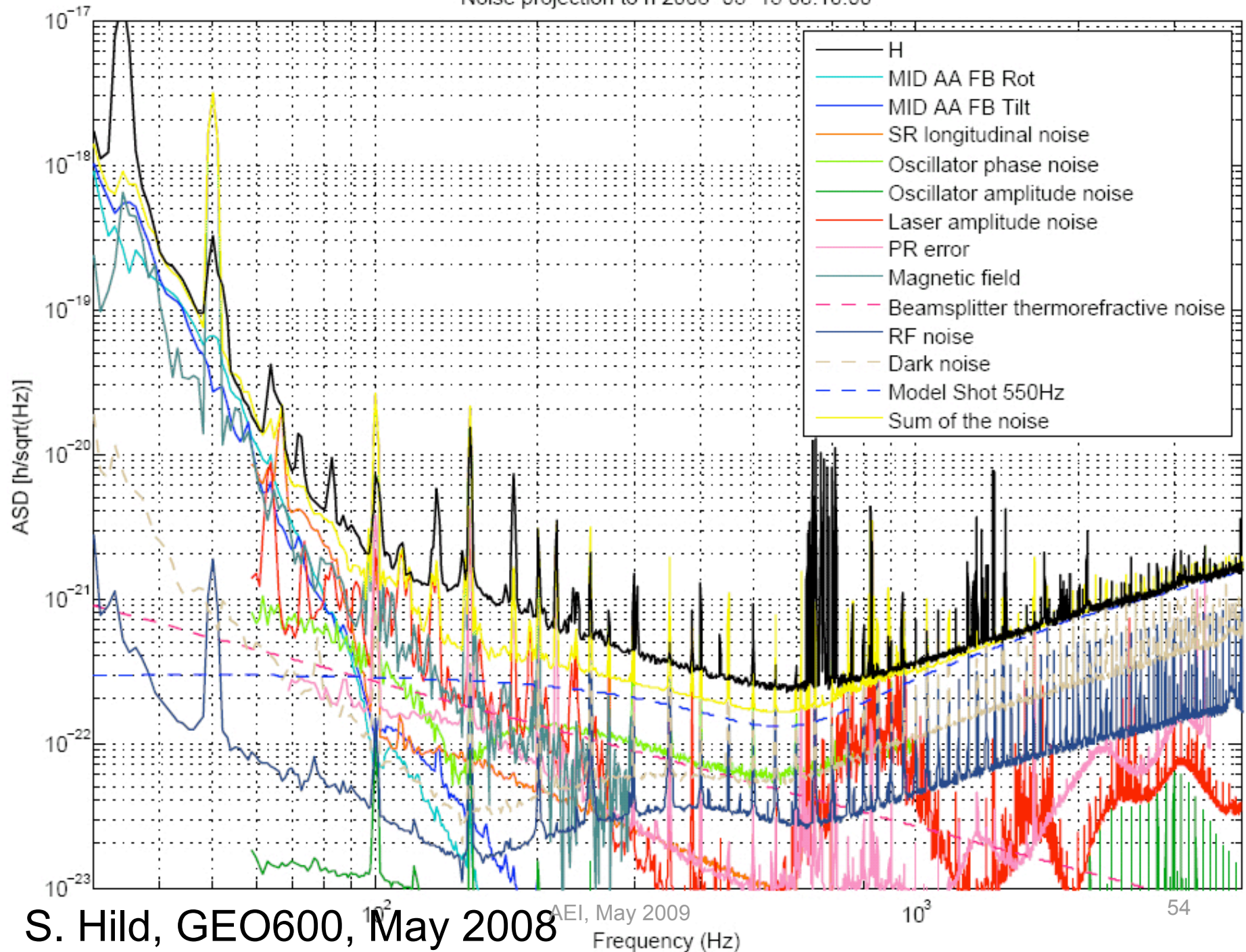
K.Strain



H. Lück, S. Hild, K. Danzmann, K. Strain

AEI, May 2009

Noise projection to h 2008-05-15 08:10:00



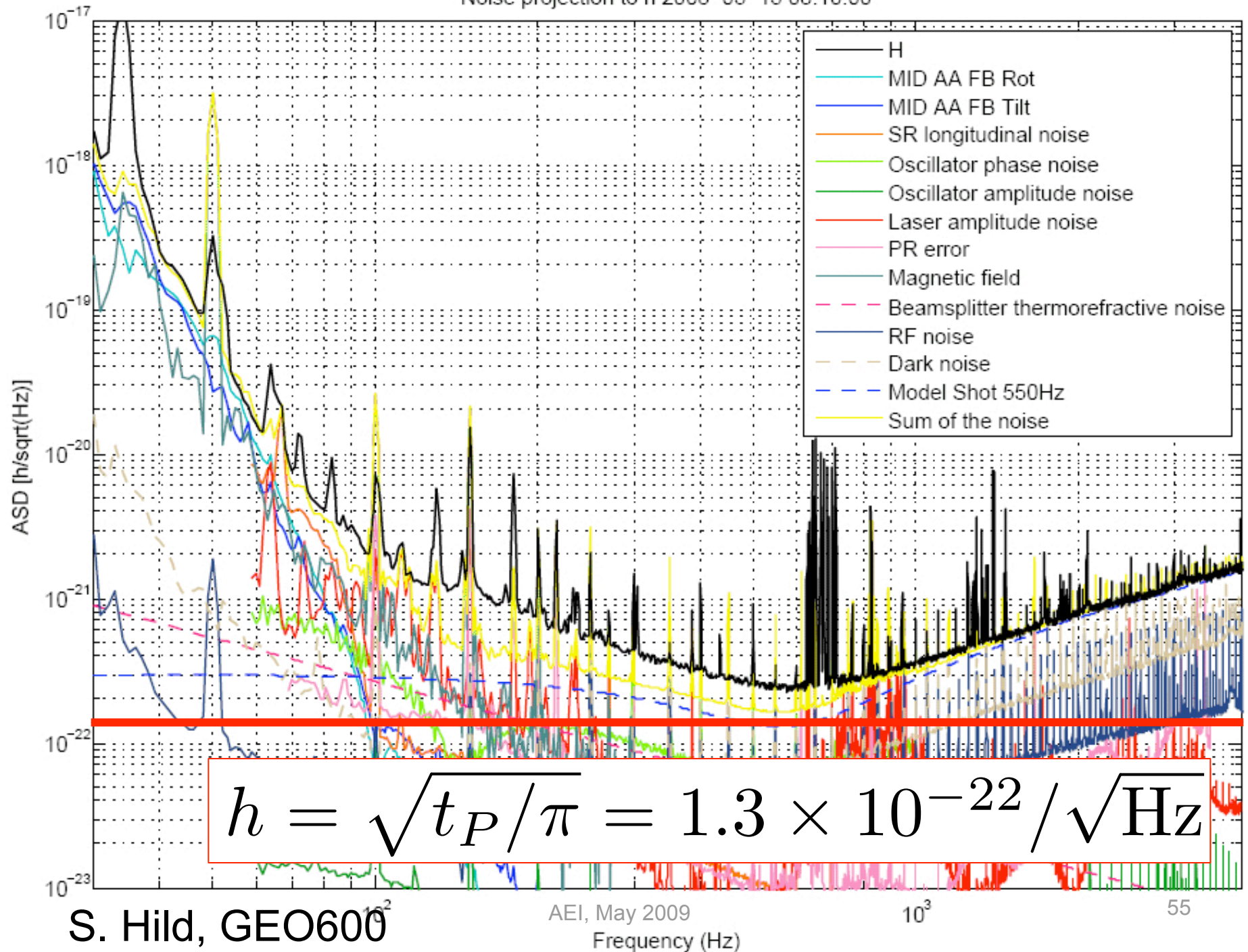
S. Hild, GEO600, May 2008

AEI, May 2009
Frequency (Hz)

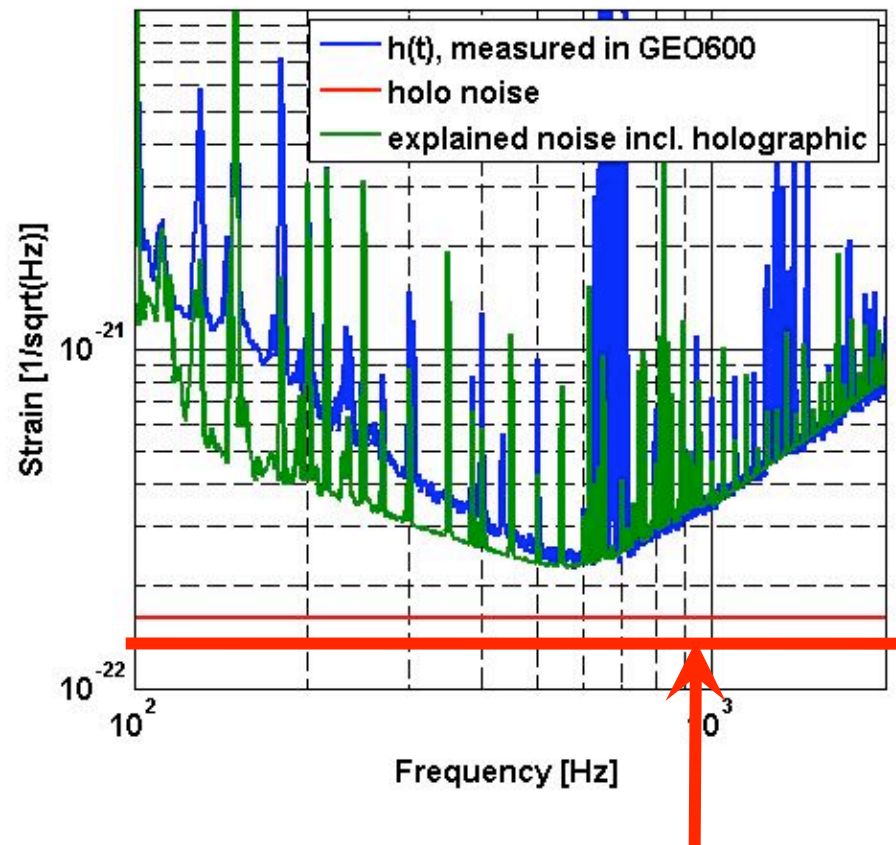
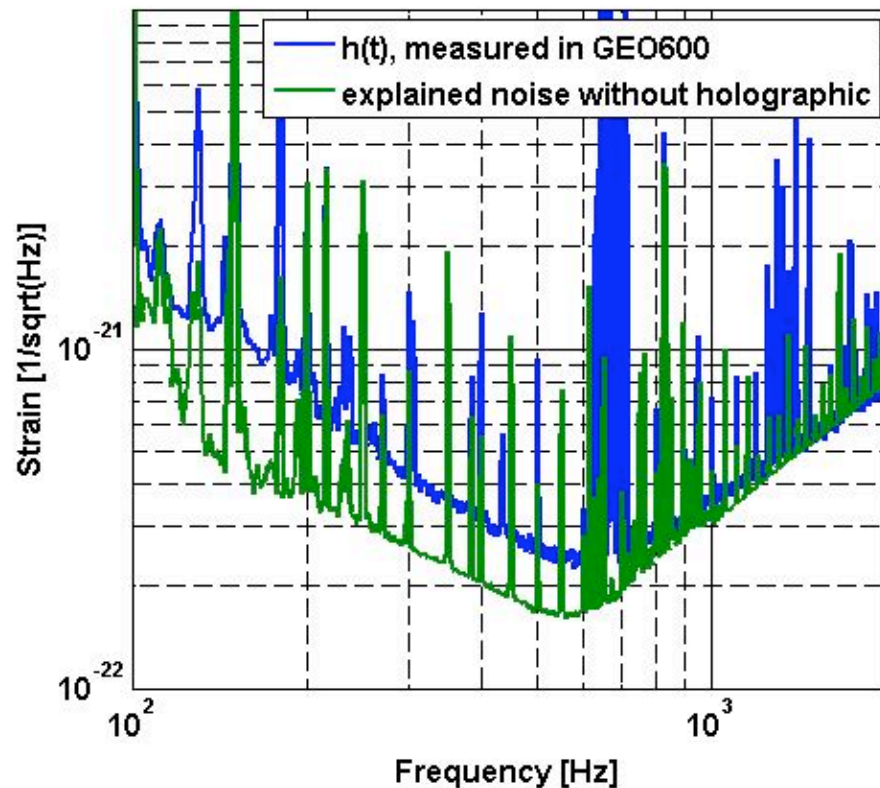
10^3

54

Noise projection to h 2008-05-15 08:10:00



“Mystery Noise” in GEO600



$$\sqrt{t_{Planck} / \pi}$$

Data: S. Hild (GEO600)

Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

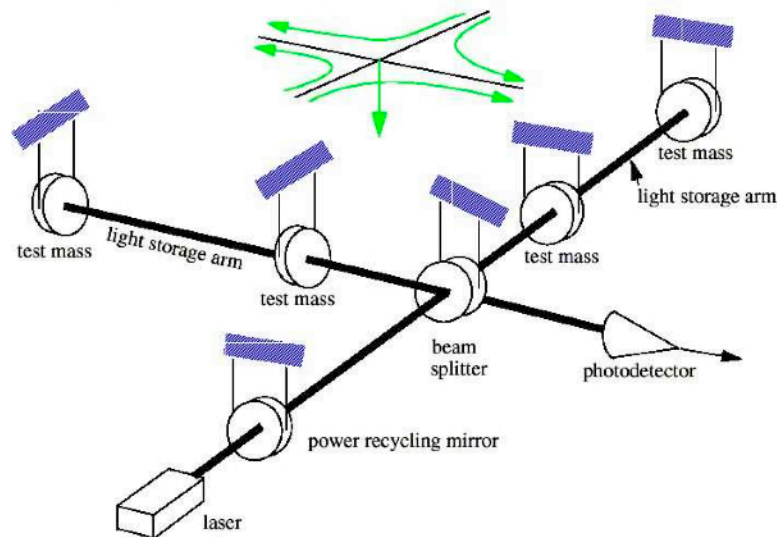
zero-parameter prediction for
holographic noise in GEO600
(equivalent GW strain)

Total noise: not fitted

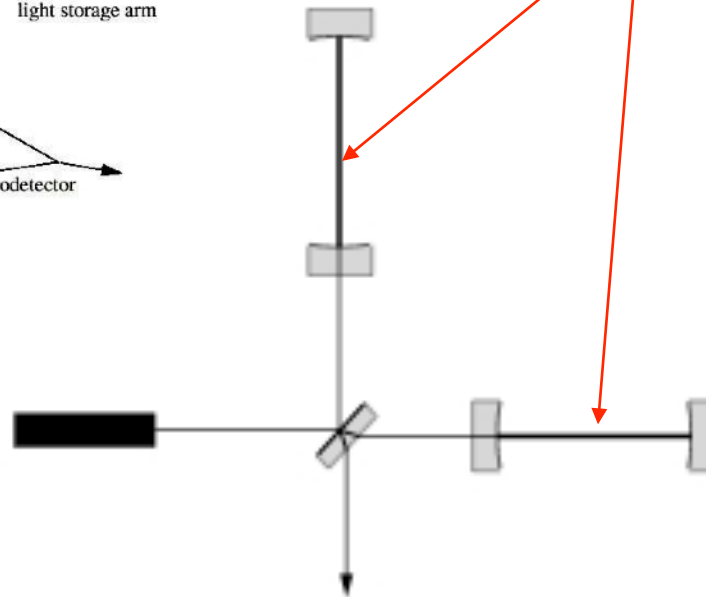
Why doesn't LIGO detect holographic noise?

- LIGO design is not as sensitive to transverse displacement noise as GEO600
- relationship of holographic to gravitational wave depends on details of the system layout

Fig. 1. Schematic layout of a LIGO interferometer.



Transverse position measurement is not made in FP cavities



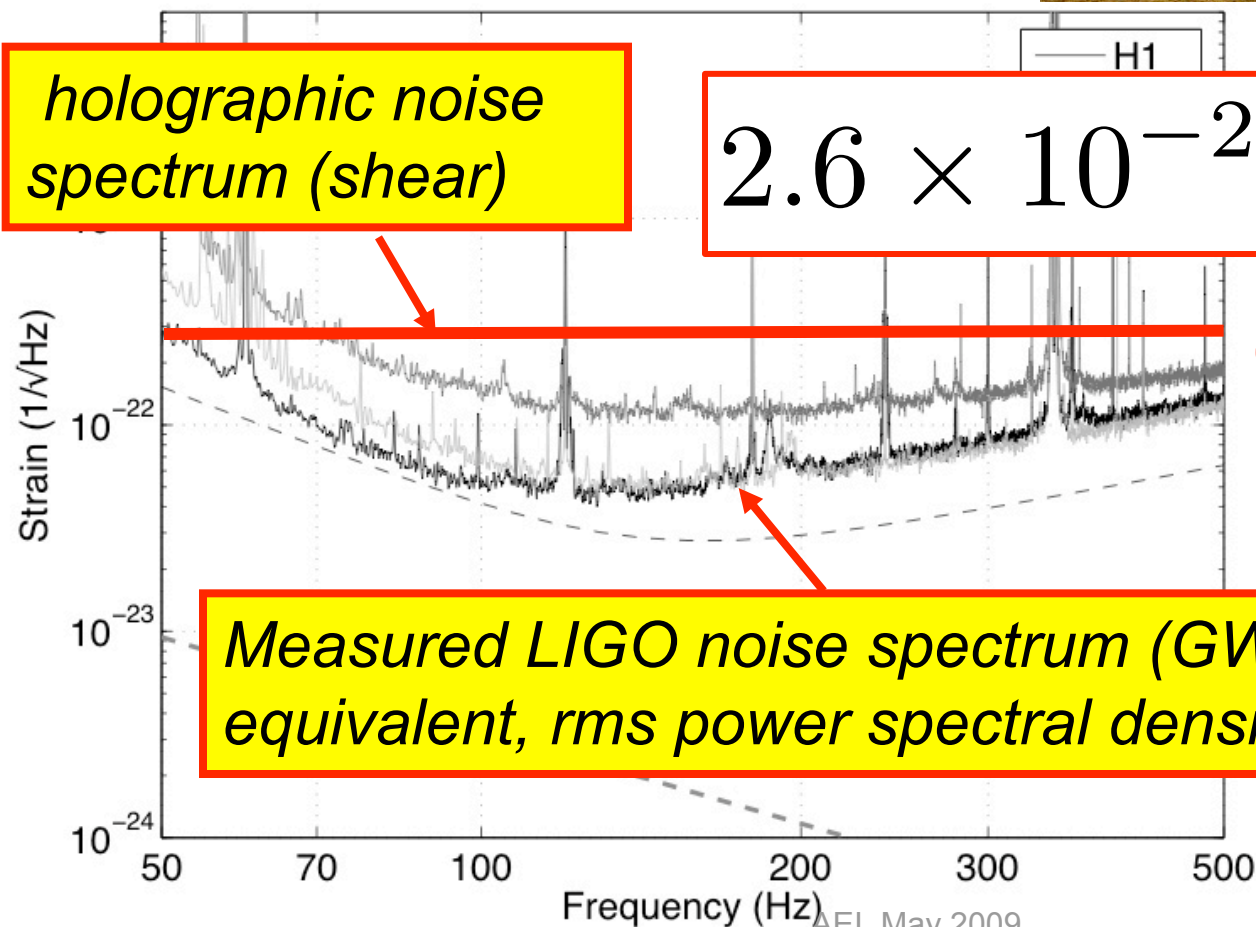
LIGO noise (astro-ph/0608606)



holographic noise spectrum (shear)

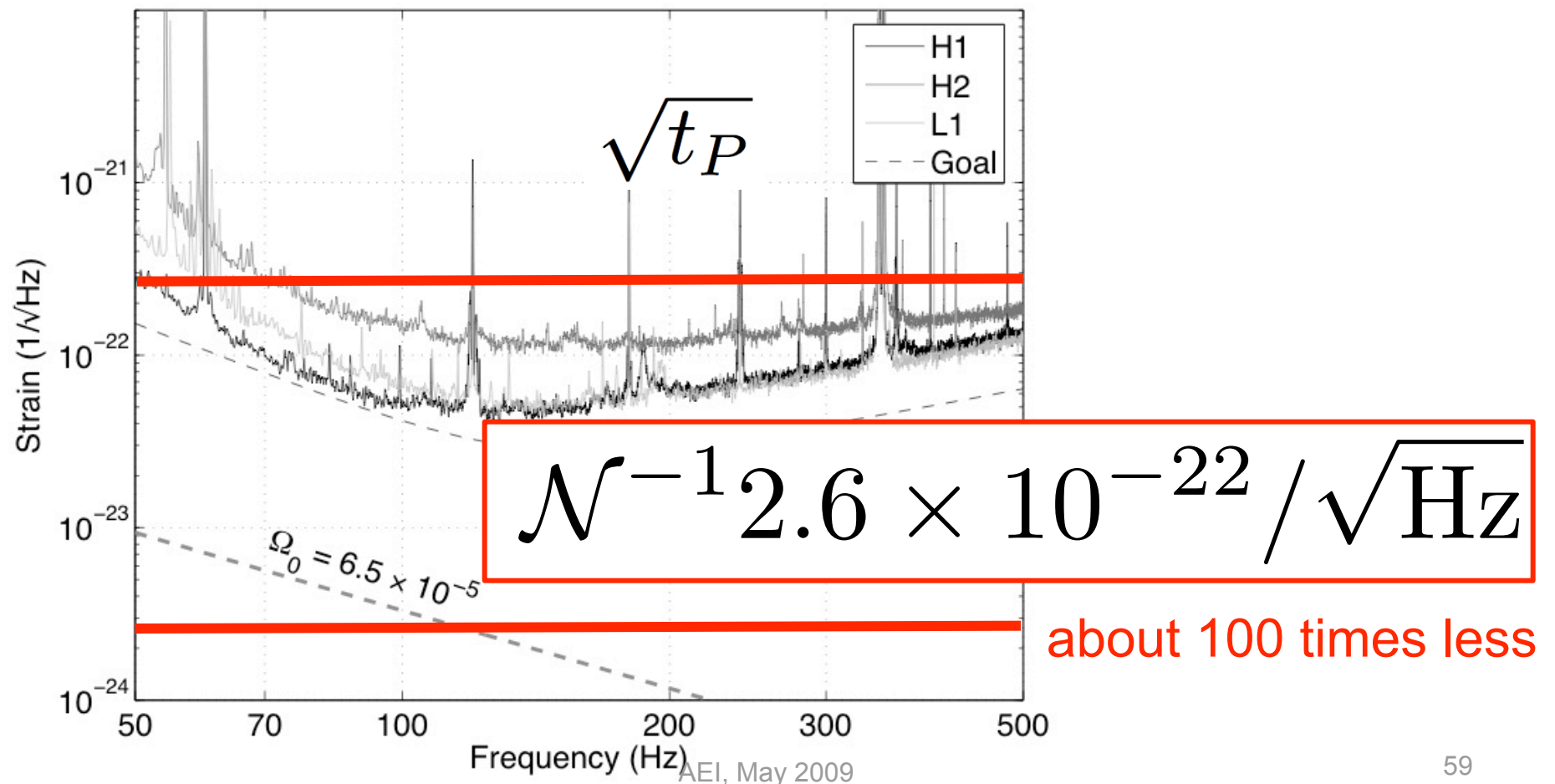
$$2.6 \times 10^{-22} / \sqrt{\text{Hz}}$$

(if shear=strain)



Measured LIGO noise spectrum (GW strain equivalent, rms power spectral density)

holographic noise prediction for LIGO: reduced by
 \sim arm cavity finesse



Interferometers can detect quantum indeterminacy of holographic geometry

- Beamsplitter position indeterminacy inserts holographic noise into signal
- **system with GEO600 technology can detect holographic noise if it exists**
- Signatures: spectrum, spatial shear

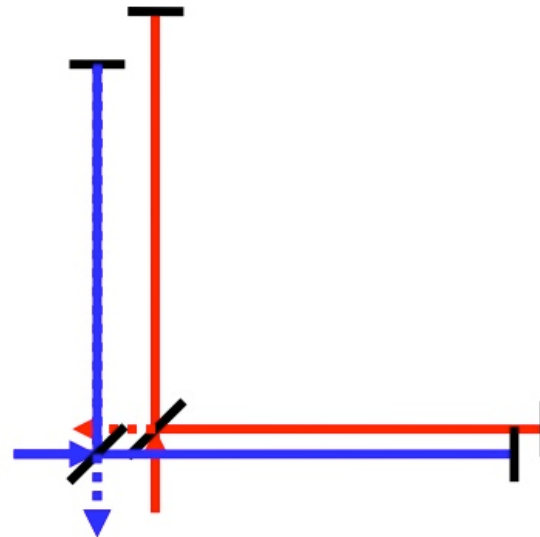
CJH: Phys. Rev. D 77, 104031 (2008); [arXiv:0806.0665](https://arxiv.org/abs/0806.0665)

Current experiments: summary

- Most sensitive device, GEO600, sees noise compatible with holographic spacetime indeterminacy
- requires testing and confirmation!
- H. Lück: "...it is way too early to claim we might have seen something."
- But GEO600 is operating at holographic noise limit
- LIGO: current system not sensitive enough, awaits upgrade
- Proof: new apparatus, coherence of adjacent systems

Dedicated holographic noise experiments: beyond GW detectors

- $f \sim 100$ to 1000 Hz with GW machines
- $f \sim 3$ MHz possible with new apparatus on ~ 40 m scale
- Easier suspension, isolation, optics, vacuum, smaller scale
- Correlated holographic noise in adjacent paths:
signature of holographic effect

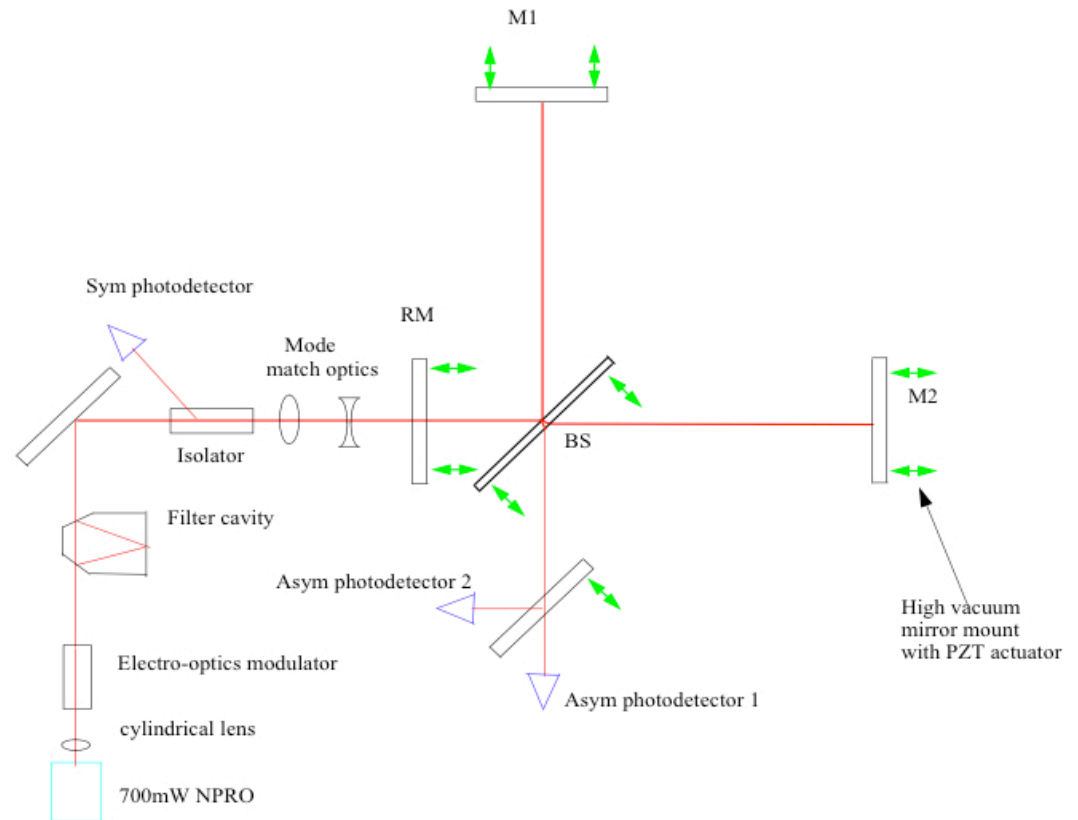


Conceptual Design from Rai Weiss

Two ~40m Michelson
interferometers in
coincidence

~1000 W cavity

holographic noise= laser
photon shot noise in ~5
minutes (1 sigma)

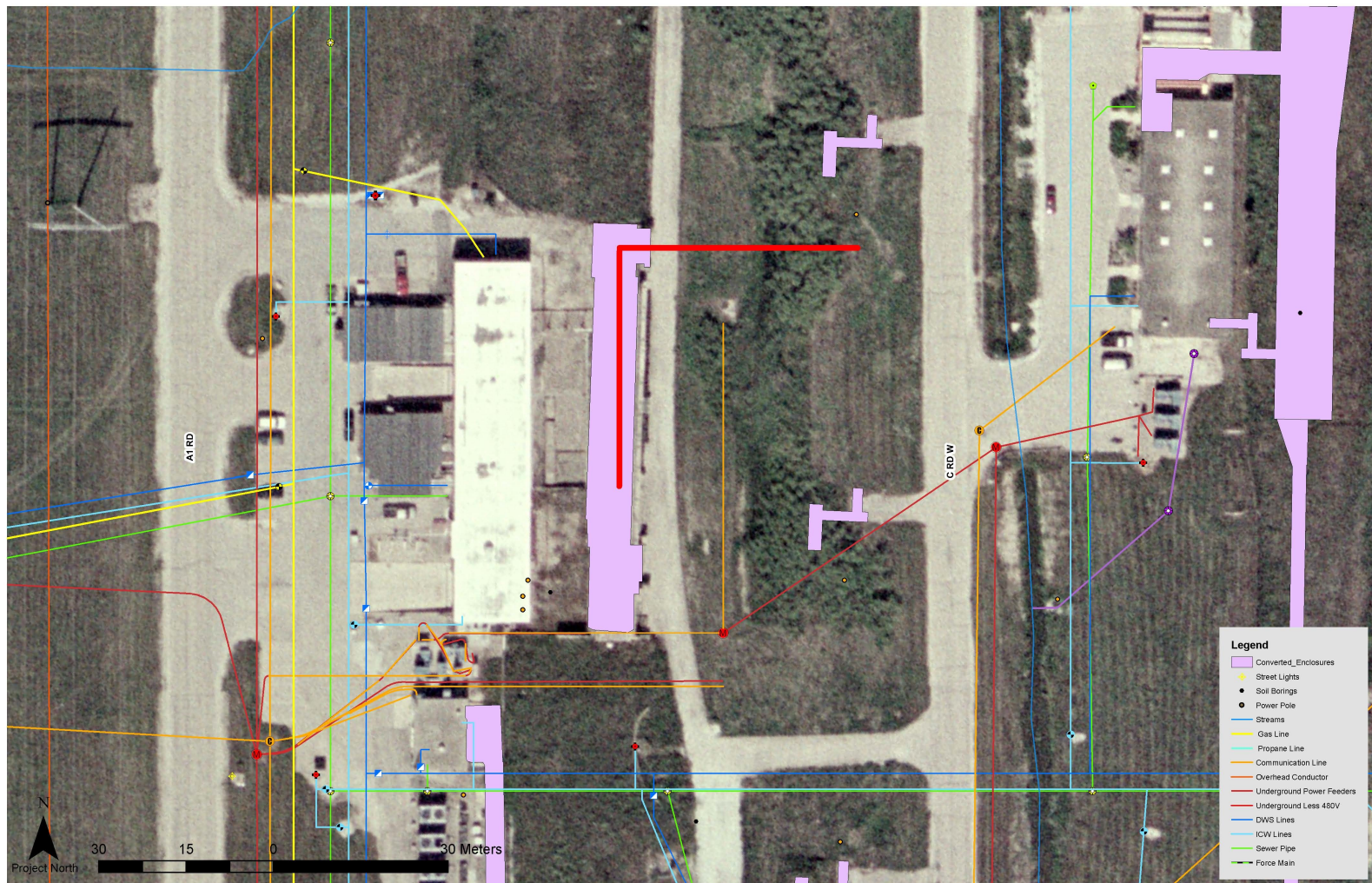


Currently discussing: Fermilab (CJH, Chou, Wester, Steffen, Ramberg, Gustafson, Stoughton, Tomlin, Ruan, Bhat), MIT (Weiss, Waldman), Caltech (Whitcomb), UC (Meyer)

Status of the Fermilab Holographic Interferometer

- Team so far: Fermilab (CJH, Chou, Wester, Steffen, Ramberg, Gustafson, Stoughton, Tomlin, Ruan, Bhat), MIT (Weiss, Waldman), Caltech (Whitcomb), UC (Meyer)
- Building tabletop prototype
- Planning around Weiss design
- Sites on site available and surveyed: ~40m arms possible (partially outdoors), seismically acceptable
- Invited by Director Oddone to move forward
- Internal R&D proposal in preparation, decision in ~June

Candidate site on old neutrino beamline



Science of Holographic Noise

- Measure fundamental interval of time
- Measure all physical degrees of freedom: explore physics “from above”
- Study holographic relationship between space and time, emergence of spatial dimensions
- Precisely compare noise spectrum with Planck time derived from Newton’s G : test fundamental theory
- Test predictions for spectrum and spatial correlations: properties of holographic geometry

Projects in phenomenology

- Calculate spectrum via a different argument
- Exact numerics of black hole/flat space system: normalization of value of effective λ to black hole physics
- Full quantum wave model of apparatus, spacetime, signal
- Numerically evaluate displacement spectrum at all f
- Numerically evaluate signal spectrum from displacement correlation function for various devices
- Develop theory of cross correlation for arbitrary interferometer offsets and orientations, numerical predictions

Projects in Theory

- Use Matrix theory interpretation to bridge to strings
- Secure lambda normalization to black hole entropy
- Generalize to curved spacetime backgrounds
- What happens inside black holes
- Relation to field theory
- Effect on inflationary modes (scalar, vector, tensor)
- Effect on quantum field modes (zero point energy)
- Cosmological observables (CMB, DE)
- Corrections to quantum processes
- Effect for masses less than M_P (atom interferometers)

Holographic geometry: part of new dark energy physics?

- Holographic blurring is $\sim 0.1\text{mm}$ at the Hubble length
- $\sim (0.1\text{mm})^{-4}$ is the dark energy density
- “Nonlocality length” for dark energy is holographic displacement uncertainty, scaled to Hubble length
- (literature on “holographic dark energy” centers on same numerology)
- Does not “explain” dark energy!

Items to discuss at the Hannover workshop

- What is the status of the GEO600 “mystery noise”?
- What are the prospects for GEO600 to test the holographic noise hypothesis?
- Are the theoretical arguments strong enough to motivate a new, dedicated high-frequency experiment, independent of the results from GEO600?
- What are the optimal design choices? (configuration, size, power,...)
- Will there be two experiments? (Fermilab and Hannover?)
- If so, what will be the similarities and differences between them?
- What about LIGO?